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HARD ROCK TUNNELING SYSTEM EVALUATION AND COMPUTER SIMULATION

Semiannual Technical Report

by

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September 1971

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13. ABSTRACT

An analysis of underground excavation is presented. Tunneling is emphasized because it is shown that tunneling is the major part of military and civil defense projects specifying underground facilities.

The factors which affect the design and performance of an excavation system are discussed. Geological prediction techniques and research are surveyed to identify promise of measurable improvement.

An approach to modeling the tunneling process is developed; this formulates a modular structure of a computer simulation to represent any one of many excavation system possibilities. The first set of mathematical relationships which model rock fragmentation by boring machine, drill-and-blast, pellet impact, and water jet are derived.

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SYSTEM EVALUATION AND COMPUTER SIMULATION

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FOREWORD

This semiannual report on a systems study and computer simulation of rapid underground excavation, prepared by staff members of General Research Corporation (GRC), documents Phase I of a contract which is part of the Advanced Research Projects Agency's (ARPA) program in rock mechanics and rapid excavation.

GRC's major tasks in this program include the following:

1. Identification of military and national defense needs for rapid excavation
2. General investigation of the nature of the excavation process in itself, and as an element in the total underground construction setting
3. Functional breakdown of the excavation process into its basic elements, and an analysis of these elements to establish mathematical representations of performance and cost, as well as interelemental relationships
4. Development of a computer simulation to estimate the performance and cost of alternative excavation methods including conventional and some novel and advanced techniques

This paper reports on items 1 and 2, and also those portions of 3 and 4 completed during the first half year of the program.

ABSTRACT

An analysis of underground excavation is presented. Tunneling is emphasized because it is shown that tunneling is the major part of military and civil defense projects specifying underground facilities.

The factors which affect the design and performance of an excavation system are discussed. Geological prediction techniques and research are surveyed to identify promise of measurable improvement.

An approach to modeling the tunneling process is developed; this formulates a modular structure of a computer simulation to represent any one of many excavation system possibilities. The first set of mathematical relationships which model rock fragmentation by boring machine, drill-and-blast, pellet impact, and water jet are derived.

CONTENTS

FIGURES

FIGURES (Continued)

TABLES

SUMMARY

This report covers three areas of investigation: military and civil defense needs for underground excavation, evaluation of systems for hard rock tunneling, and computer simulation of tunneling, related geology, and related cost accounting. The investigation focuses on the cost and methods of tunneling. The overall purpose is to identify and provide a framework suitable for evaluating the cost and merits of various hard rock tunneling systems and to determine quantitatively the increased excavation capability which may be possible through improvements in excavation technology, rock mechanics knowledge, and geological exploration capability. A primary objective of this research program is to identify specific systems which may be substantially faster and more economical for underground excavation of hard rock than those utilized in the past.

A preliminary step was to survey and outline military and national defense requirements for underground excavation; the purpose here was to identify the major type of excavation planned for the coming decade. Section II briefly reviews this survey and identifies tunneling, as opposed to shaft or cavern excavation, to be of primary interest. Because improvements in tunneling constitute the greatest need and offer the greatest reward in time and money if the projects surveyed continue beyond planning into the construction stage, it was decided to concentrate the subsequent analysis and computer simulation on those excavation systems most suitable for tunneling in rock.

To establish a perspective for the analysis of tunneling systems, the authors discuss in Sec. III the overall nature and general setting of the problem including the many factors (external to the tunneling system itself) that can affect tunneling cost and performance. One, geological surveying and prediction, significantly affects the design of both the tunnel and the excavation system. Another, labor costs, often exceed 50% of the total cost of a given project, and can be greatly affected by such factors as

labor availability and project location (i.e., up to a threefold increase in labor costs has been observed in an urban environment compared to rural areas). Other external factors such as the availability of equipment, the accessibility of the site, the depth of the tunnel, the legal and organizational considerations, and even the flexibility of the completion date can also impact significantly on overall system cost and performance.

The importance of improving geological prediction techniques is further discussed in Sec. III-C. Current techniques are still far from able to provide adequate information about geological conditions, either before or during excavation, but advancement of some present techniques plus the promise of a number of advanced ones should provide measurable improvement.

In Sec. IV the authors present a computer model of the excavation process which will aid the evaluation of alternative tunneling systems. The basic structure consists of (1) a geology model to produce detailed and consistent representations of realistically complex geologies; (2) a tunneling model which is used to simulate any one of many excavation systems; and (3) a cost accounting and reporting system.

A significant feature of the model is its modularity. Each of the various activities performed during tunneling is modeled by a subroutine which calculates the cost and effect on the overall performance of that activity. Both conventional and advanced techniques can be simulated. The sequencing of these activities (subroutines) to simulate the total tunneling procedure is controlled by a general program. By access to common information files this control program also accounts for interaction between activities.

Tunneling processes which are to be included in the model (Table 11 of the text) include both current and advanced methods suitable for hard rock excavation. Four of these processes represent alternative methods of fragmenting rock (i.e., drill-and-blast, boring machine, water jet, and

pellet impact). They have been investigated to identify the activities associated with each process and the typical performance and cost relationships.

Projected work in the second half of this first year's effort will similarly identify the functional relationships for materials handling, ground support, and environmental control.

In brief, this report presents a perspective of the excavation process, formulates the concept and structure of a computer simulation which can represent any one of many excavation system possibilities, and identifies the first set of mathematical relationships to be incorporated into this simulation.

I. INTRODUCTION

Current capabilities for excavation seem to be limited to 200-300 ft per day in soft rock by mechanical borer and 70 ft per day in hard rock by drill-and-blast technique. Because future civilian and military requirements for excavation may demand rates two to three times more rapid than is presently possible and would require lower unit costs than are now attainable, an expanded research program to improve rapid excavation* techniques is being supported by the Advanced Research Projects Agency (ARPA) and managed by the U.S. Bureau of Mines.

This need for improved underground excavation techniques has been documented in recent reports of studies undertaken by the National Research Council,[1,2] the Organization for Economic Cooperation and Development (OECD),[3] and many other groups.[4] The National Research Council has forecast that if industrial and governmental research and development were to continue at the levels and in the direction of past efforts, real costs of underground excavation would not be significantly reduced. Sustained rates of advance would rise only 100% in soft-medium rock and 33% in hard rock over the next 20 years.[1] The ARPA rock mechanics and rapid excavation program is a step toward an expanded research program which, the Council estimates, could provide the base of knowledge needed for achieving a 30%-50% reduction of cost and a trebling of the sustained rate of advance of excavation.

ARPA program emphasis was developed, in part, from the National Academy of Sciences Publication 1969, "National Research Council Committee on Rapid Excavation Report, Rapid Excavation - Significance - Needs -

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*The term "rapid excavation" is usually left undefined. The authors interpret rapid excavation systems to mean technology with the potential of a 30%-50% reduction of cost and a three-fold improvement in rate of advance if compared to 1970 capability.

Opportunities."[1] This program comprises research topics in the following seven areas:

Rock and earth material disintegration

Rock properties and state of stress measurements

Geologic prediction

Ground support

Materials handling

Fundamental studies in rock mechanics

Systems analysis

As participants in the ARPA program, staff members of General Research Corporation (GRC) are in the process of analyzing rapid excavation systems and techniques. They have the goal of developing a computer simulation that combines all of the various elements which make up an excavation system into a total system model. The model will be used to identify the possibilities of gains in total performance and reductions in overall cost by improvements resulting from each of the six areas of research.

This report describes the approach taken, information gathered, and results obtained during Phase I of this effort.

II. MILITARY REQUIREMENTS FOR RAPID EXCAVATION

A. INTRODUCTION AND SUMMARY

This chapter, which outlines military and national defense requirements for rapid excavation in hard rock, reports the first step taken in GRC's program to develop a systems model of the excavation process. This study was designed to determine which category of underground excavation (tunnel, cavern, or shaft) should receive first emphasis and be studied in detail through systems modeling. The criteria used in making this determination included:

1. Greatest need
2. Potential benefit
3. Success of modeling
4. Availability of technical information and expertise

The available information and expertise on each type of excavation seemed sufficient to guarantee comparable success in the systems modeling task. Consequently, greatest need and potential benefit became the dominant factors in selecting an excavation category.

In virtually all of the large-scale excavation programs examined, more than one category of excavation is required and more often than not all three types of excavation are needed. However, because it was necessary to limit the scope of the overall program at this time, this chapter shows that improvements in the tunneling process constituted the greatest need and also offered the most significant benefits in terms of time and money. In most major excavation systems studies, tunneling-related costs comprise the largest percentage of the total cost of excavation and are usually twice as expensive as either of the other types.

In the next section several significant military and national defense excavation projects are examined and their highlights presented.* Some of these projects are currently topics of much deliberation; others are already in progress or have been canceled because they were too expensive.

One point was made very clear during the course of this study: significant improvements in rapid excavation of hard rock are essential if the military is to capitalize on the many advantages offered by subsurface systems. The vast amounts of time and money required for many of these excavations are prohibitive and consequently limit the decision criteria on the utility of such a system to one of cost alone rather than cost-benefit combined.

B. RAPID EXCAVATION PROJECTS

Military and national defense uses of underground excavations usually fall into one of the following categories:

1. Command centers
2. Communication facilities
3. Missile basing systems
4. Weapons testing
5. Civil defense

The primary reason for placing military facilities underground is for protection against a direct attack. Highly accurate weapon delivery is required to destroy most subsurface installations. If the exact location of the facility is kept secret, any potential enemy is faced with

*A classified version of this chapter can be found in the report Military Requirements for Rapid Excavation (U), IMR 1489, by Stuart Rubens, General Research Corporation, March 1971 (SECRET). This report goes into greater detail on the purposes behind the various military projects presented.

an even more difficult targeting problem. The subsurface also affords the opportunity to use deception as a tactic thereby extracting a far greater price from the offense than would normally be required.

The first two projects discussed in this section are currently under study by the military and consequently are classified. These projects will be referred to as Site A and Site B.

1. Site A[5]

Site A is an underground facility to be located in hard rock at a depth of roughly one mile. A central facility, consisting of several large caverns which contain buildings for manned operation, is the nucleus for a network of communications tunnels and access-egress shafts.

Approximately 2,000,000 cubic yards of rock would be excavated, including over 20 miles of tunnels and almost 10 miles of shafts. The total cost of the excavation was estimated at $265,214,000, and would require 66 months of operation, 6 days per week, 24 hours per day.[6]

The majority of the excavation is presumed to utilize conventional drill-and-blast methods. Table 1 summarizes the direct costs* associated with this system broken down by type of excavation.

*Direct cost excludes such items as overhead and profit.

TABLE 1

SUMMARY OF DIRECT COSTS ASSOCIATED WITH SITE A

Category	Direct Cost ($)	Total (%)
Shafts	56,886,818	28.80
Tunnels	103,335,958	52.31
Cavity	16,040,636	8.12
Other (hardening, access facilities)	21,278,284	10.77
Total	197,541,696	100.00

2. Site B[7]

Site B is a communications facility which involves the deployment of a huge antenna system deep underground. To jointly satisfy survivability and electronics requirements, the present plan has the system located in granite with a high compressive strength. It is anticipated that over 100 miles of antenna tunnels will be required. Table 2 presents the primary dimensions of the system and the excavation requirements.

TABLE 2

EXCAVATION REQUIREMENTS FOR SITE B

	Main Gallery	Heat Sink	Antenna & Ground Tunnels	Main Access Shaft
Cross Section	Elliptical	Elliptical	Circular	Rectangular
Dimensions	166×112 ft	166×112 ft	13 ft dia.	20×50 ft
Length	1110 ft	675 ft	114 mi	~6000 ft
Excav. (cu yd)	~556,000	~338,000	~3,000,000	~225,000

All excavation will be done using conventional drill-and-blast techniques, except for the vent shafts which will be drilled by big-hole drilling methods. The cost of drill-and-blast techniques versus tunnel boring machines was compared assuming current state-of-the-art capability for each technique. Drill-and-blast would progress at an estimate 58.4 linear feet per day at a direct cost of $33.86 per cubic yard, and tunnel boring at 45 linear feet per day at a direct cost of roughly $40.00 per cubic yard (estimated). The total cost of the excavation was estimated at $530,018,000.[6] The job would take over 95 months on a 24-hour, 6-day work schedule. Approximately 4.7 million cubic yards of granite would be excavated. A summary of direct costs associated with the Site B project are presented in Table 3 according to excavation category.

TABLE 3

SUMMARY OF DIRECT COSTS ASSOCIATED WITH SITE B

	Direct Cost ($)	Total (%)
Shafts	69,036,725	17.33
Tunnels	125,994,973	31.63
Cavity	65,711,666	16.50
Other		
(antena grid, hardening, site work)	137,561,610	34.54
Total	398,304,974	100.00

3. NORAD Expansion[8]

The Army Corps of Engineers is currently excavating for the expansion of the NORAD Cheyenne Mountain Complex (NCMC) near Colorado Springs, Colorado. Approximately 60,000 cubic yards of rock will be excavated within the one-year duration of the project. The rock is primarily granite with an average compressive strength of 18,000-21,000 psi, with a spread from 10,000 psi to greater than 30,000 psi. Since the tunnels are not straight, the entire excavation will be conventional drill-and-blast, except for a small amount of raise-boring by machine.

A cost breakdown by category for this project is presented in Table 4. The category "Tunnels, Chambers, Adits" was not broken down further in the government estimate because each excavation will be performed in a similar manner and the contractor will be paid according to the total cubic yards removed.

TABLE 4

SUMMARY OF DIRECT COSTS ASSOCIATED WITH THE NCMC EXPANSION PROJECT

	Direct Cost ($)	Total (%)
Shafts	58,950	2.22
Tunnels, chambers, adits	2,275,982	85.74
Other (mobilization, demobilization)	319,500	12.04
Total	2,654,432	100.00

4. Missile Basing

Over the past several years numerous studies have examined the advantages of deploying missile complexes underground. These concepts evolved from a desire to reduce the vulnerability of the U.S. strategic missile force to a first-strike attack. The proposed systems (all basically similar) would locate the missiles, personnel, ground equipment, and life support facilities underground at a depth ranging from 300 to 3000 feet.

Each complex would have consisted of 10-20 miles of main tunnel. Leading from the main tunnel of each complex to the launch portals would be numerous spur tunnels each roughly 1/2 mile long. Missiles could be randomly stored on transporter-launchers in the main tunnel, in spur tunnels, or at the launch portals. This random deployment would deny the enemy an accurate target point. Figure 1 presents a schematic of one missile-basing configuration.

A breakdown of excavation costs by category was not available; however, one system which was proposed required over 1500 miles of tunnels. The excavation was estimated to cost $3.5 billion.

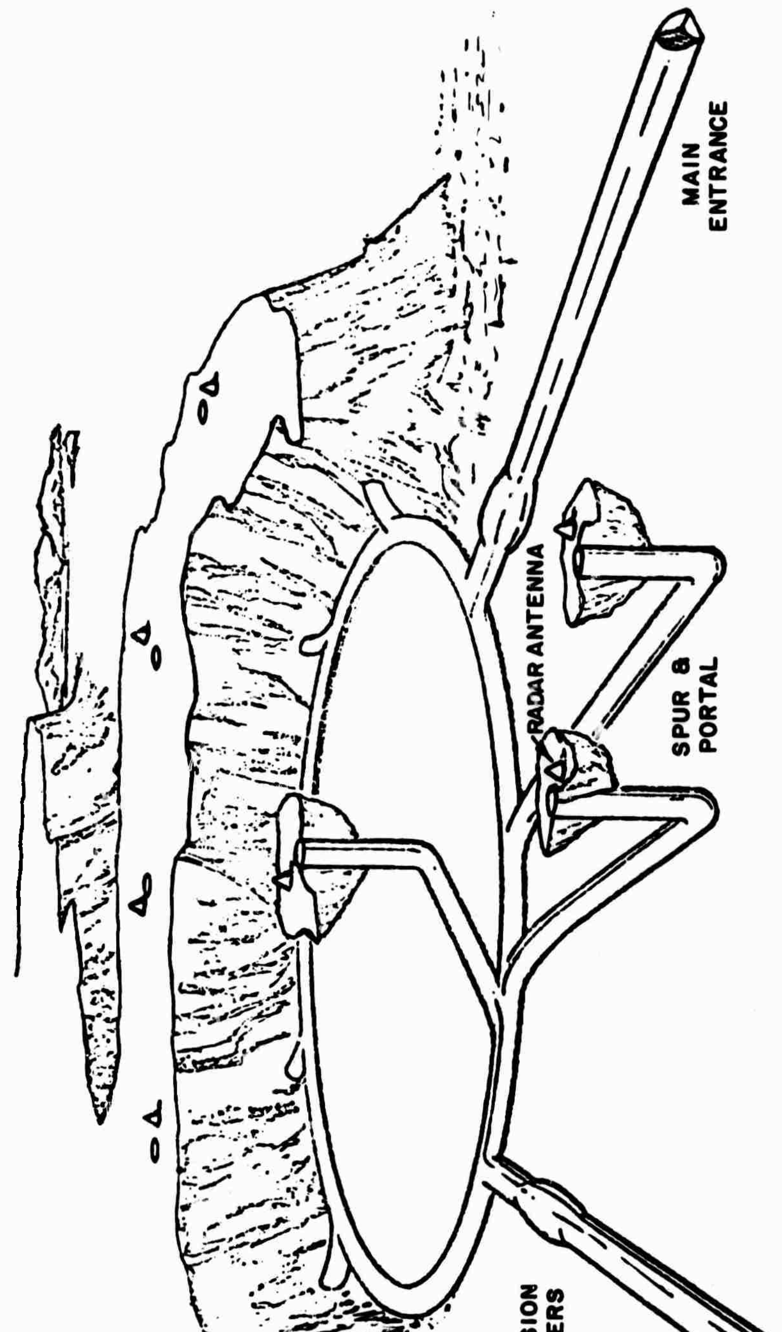


Figure 1. Missile Basing Concept

5. Weapons Testing[9]

The Atomic Energy Commission (AEC) has performed more large-shaft drilling than any other organization in the world. The majority of these shafts are used in the nuclear weapons testing programs. The AEC has been averaging 40-50 tests each year. The material excavated is primarily welded tuff (10,000-20,000 psi) and silicified rhyolite (20,000-30,000 psi). The average shaft is drilled to a diameter of 60 inches and a depth of roughly 2000 feet. The AEC has also excavated a 120-inch shaft, which is the largest ever drilled.

The most ambitious excavation program undertaken by the AEC is currently in progress on Amchitka Island off the coast of Alaska. Weapons with yields in excess of 1 megaton are being tested under simulated atmospheric conditions. The project involves the drilling of 90-inch shafts to a depth greater than 6000 feet. A 50-foot-diameter cavity is then excavated at the bottom of the shaft by conventional drill-and-blast methods. The cavity is used to simulate atmospheric conditions. The excavated material is mostly volcanic breccia and basalt (15,000-20,000 psi). It takes approximately one year to do the excavation, and the cost is \$2-\$3 million.

Should a new large-scale testing program be required in the near future, the AEC has a plan which promises to reduce the cost of a multiple-test program. The plan involves excavating one main tunnel ($\sim$20 feet in diameter) into the side of a mountain. A series of small tunnels leading into individual caverns will be excavated from the main tunnel (see Fig. 2). One test will be conducted in each cavern. The advantages of this plan are that the main tunnel is reused and the excavation is horizontal instead of vertical.

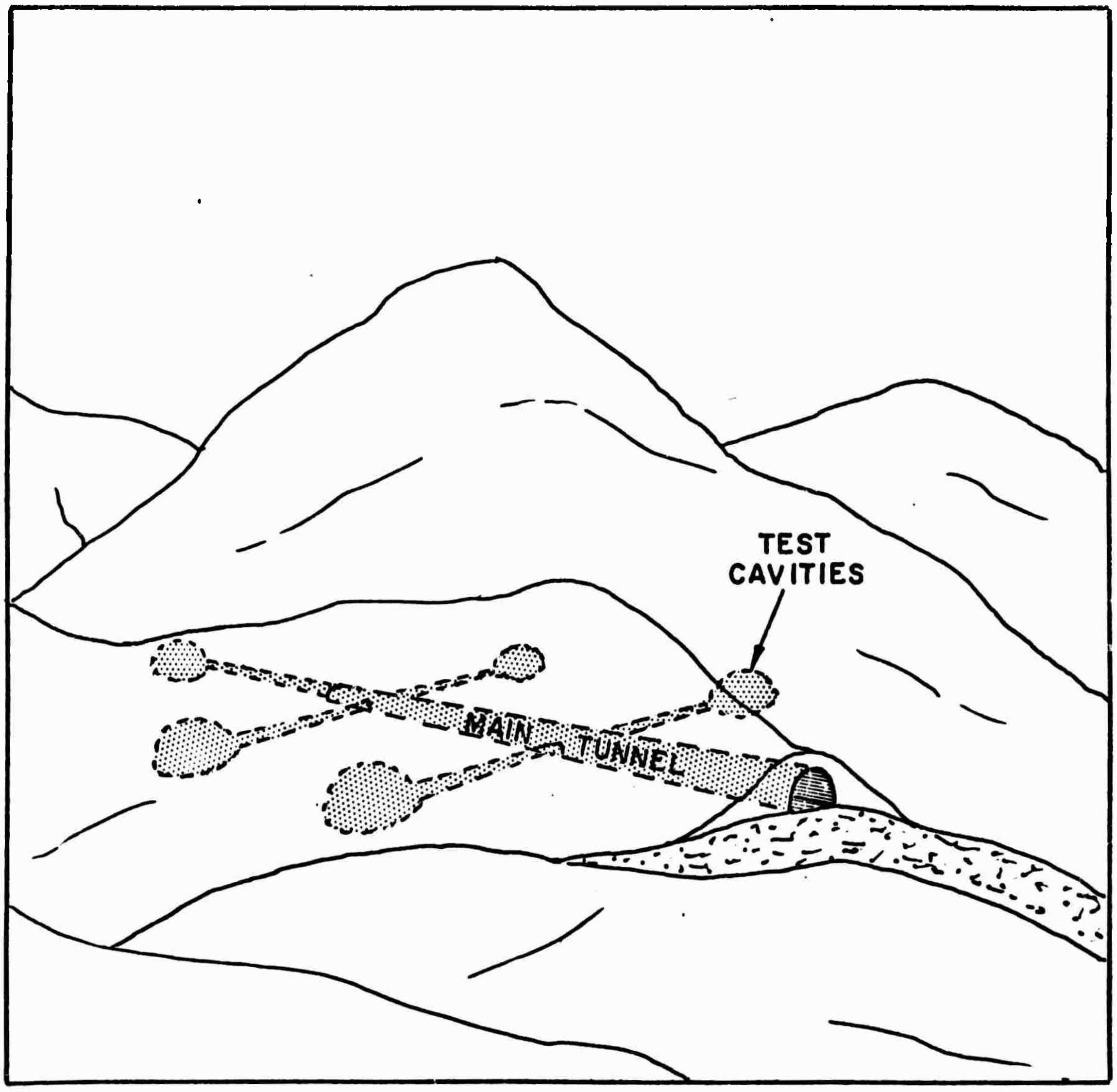


Figure 2. Proposed Weapon Testing Configuration

6. Multi-Use Tunnels for Civil Defense[10]

The feasibility and utility of multi-use tunnels have been studied, the contemplated uses being civil defense, transportation, waste removal, utility lines, and urban renewal projects. Sweden, Germany, and Switzerland have already developed many dual-purpose systems and have clearly demonstrated that this significantly reduces the cost of shelters compared to those designed only for defense.

A preliminary design study of a utility tunnel system for the White Plains, New York, Central Renewal Area considered the dual use of such tunnels as civil defense shelters. The modifications and additions required to provide this dual-use capability include entrances, blast doors, air conditioning, life support systems, and sanitary facilities.

The White Plains tunnels would provide 14 square feet of area per person for a shelter population of 5000 and 3.5 square feet for a shelter population of 20,000. Figure 3 shows a typical plan for the conversion of the 9-foot tunnels for use as civil defense shelters.

The utility tunnels as designed for White Plains have an inherent blast resistance of about 60 psi with proper design of the reinforcing steel. The addition of small amounts of reinforced concrete to the roof slab could be used to increase the blast resistance to 100 psi.

Open-trench techniques would be used to excavate the roughly 35,000 cubic yards of material for these tunnels, except where the existence of surface facilities required tunneling. The pertinent direct cost data for the dual-use utility tunnels, with a capacity for 20,000 people, is broken down in Table 5. The entire system has 7100 feet of tunnels.

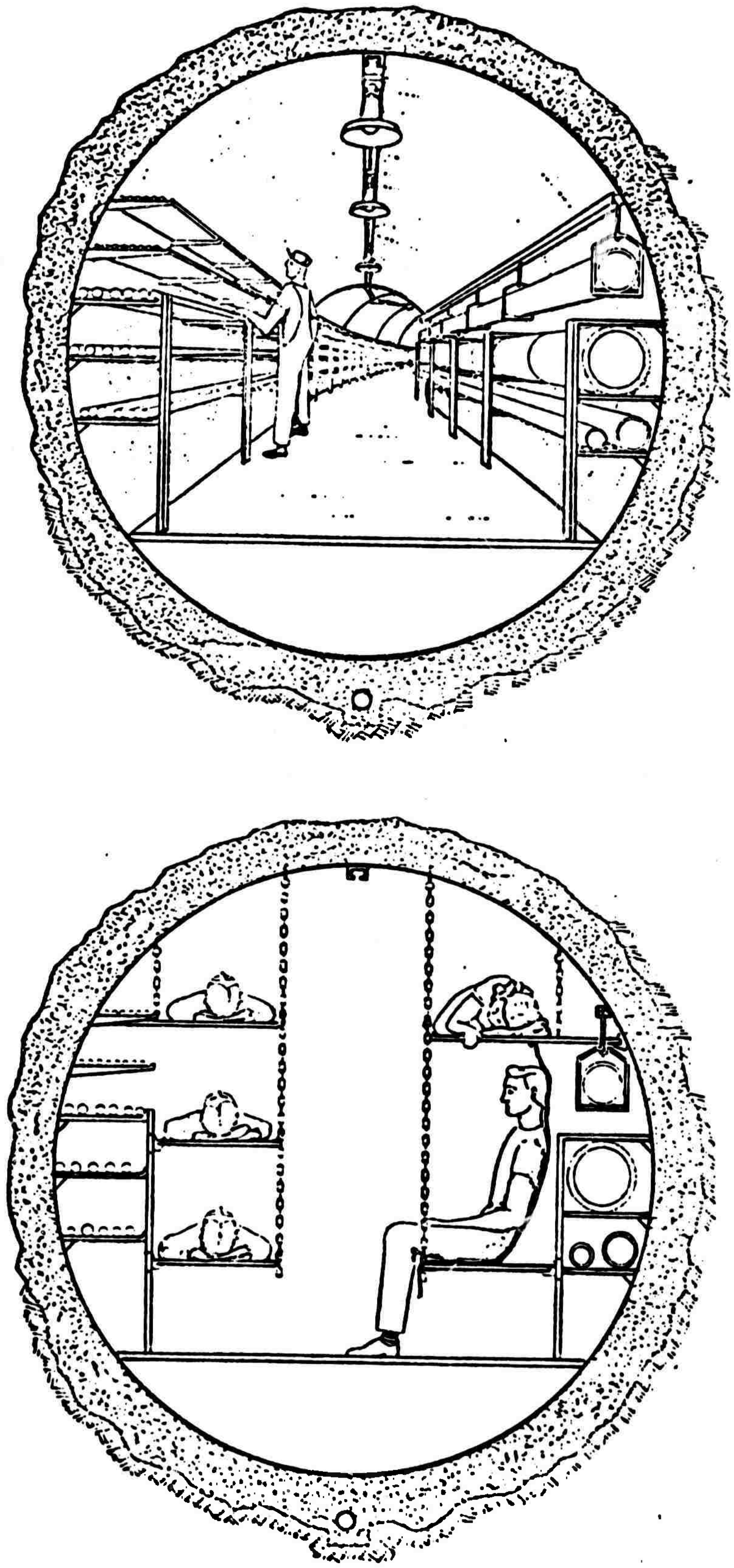


Figure 3. The Conversion of a 9-Foot Tunnel for Shelter Use

TABLE 5

DIRECT COST FOR DUAL-USE UTILITY TUNNEL BLAST SHELTER

	Direct Cost ($)	Total (%)
Excavation and backfill	1,230,000	37.44
Reinforced concrete	1,425,000	43.38
Water proofing, services installation	630,000	19.18
Total	3,285,000	100.00

C. CONCLUSION

Many military and civil defense facilities in advance planning stages call for extensive underground excavation, particularly tunneling in hard rock. Consequently, the greatest effort of systems analysis and modeling will focus on those processes suitable for tunneling in hard rock. Significant improvement in excavation capability and reduction in excavation cost is necessary if these facilities are to be constructed economically and in a reasonable period of time.

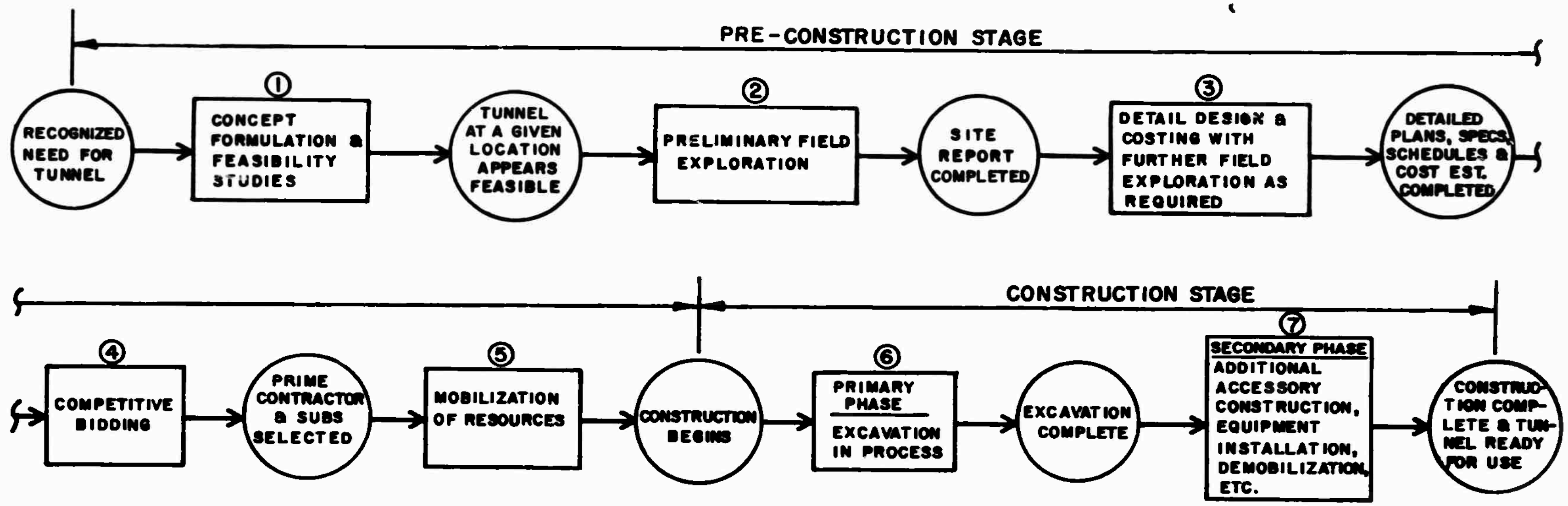
III. OVERVIEW OF UNDERGROUND CONSTRUCTION

Many factors which affect the cost and performance of a tunnel excavation system are external to the physical excavation process itself. The purpose of this section is to review these factors in general terms in order to provide a perspective of excavation as a part of the total underground construction process, and also to shed light on the nature of the excavation process itself. Acquiring an overall understanding of the problem was a major objective in the early stages of this study. This was based on the philosophy that one must first understand the fundamental nature and general setting of the problem before one can abstract a simplified model which reasonably simulates the problem's essential characteristics. Such an approach also allows one to become aware of the fundamental limitations of the model, and where future efforts should be concentrated to improve it.

A. THE EXCAVATION PROCESS IN THE TOTAL CONSTRUCTION SETTING

Figure 4 represents the sequence of milestones and activities that are typically followed in the total process of constructing a tunnel underground. One can see that, between the time a need for a tunnel is recognized and its actual completion, two broad stages are distinguishable: preconstruction followed by actual construction.

The preconstruction stage comprises mostly planning. When the need or desirability for a tunnel or network of tunnels is recognized, an official agency (e.g., ARPA if the project is military, or a state highway department if the tunnel is to be part of a highway system) will conduct concept formulation or feasibility studies (Activity No. 1 in Fig. 4). Generally, this is the first step towards assessing the overall feasibility of the proposed construction. These studies are of most value if there are alternatives to either the basic type of construction (i.e., a tunnel versus some other possibility) or perhaps the location. Thus, where in fact there are no real alternatives, as might be the case in a mining



ACTIVITY NUMBER	ACTIVITY ALSO IMPLIES	TYPICAL RESPONSIBLE AGENCY
1	PRELIMINARY DESIGN	ARPA, STATE HWY.DEPT.
2	GEOLOGIC & HYDRO-LOGIC INVESTIGATION	SPECIAL CONTRACTOR
	RESOURCE AVAILABILITY	ARPA, STATE HWY.DEPT.
3	--	CORPS OF ENGR., STATE HWY. DEPT.
4	--	DEPT. OF ARMY, STATE HWY. DEPT.
5	--	PRIME CONT. & SUBS
6	BUILDING OF ACCESS FACILITIES	PRIME CONT. & SUBS
7	--	PRIME CONT. & SUBS

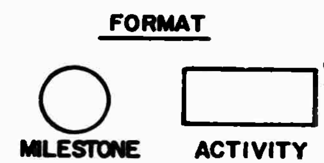


Figure 4. The Excavation Process as an Element in the Total Underground Construction Process

operation where the location of the ore body demands a tunnel at a specific location, such studies would not normally be performed.

Concept formulation and feasibility activities (if performed) include developing preliminary designs and cost estimates of the various alternatives, and then comparing their cost effectiveness. These designs and cost estimates in turn depend on studies to establish the operational requirements of the facility, and also on available information about the proposed location (including existing topological and geological maps, etc.). By their very nature these studies are limited to a relatively gross level of detail, and may also be based on incomplete information. Consequently what appears feasible in concept formulation may prove infeasible at a later date.

Once it has been decided that a tunnel at a given location appears both feasible and desirable, the responsible government agency may undertake or (if it lacks in-house capability) contract for the preliminary field exploration of the preconstruction phase (Activity No. 2 in Fig. 4). This includes geologic and hydrologic surveys of the immediate site, as well as surveys to determine the cost and availability of labor, materials, and equipment in the general area. The information acquired from these surveys forms the basis for the actual design and cost estimate of the excavation system and the overall tunnel.

Geological surveying and prediction can have a significant impact on the excavation system design and tunnel characteristics. Consequently, a more detailed look into this aspect of the preconstruction stage is presented in Sec. III-C. The reader is referred there for a discussion of the nature and objectives of geological surveying, current and future measurement procedures and techniques, and a discussion of the overall impact of uncertainties in geology on the excavation system design and performance.

Once the preliminary site report is completed, the detailed design phase of the project can begin (Activity No. 3 in Fig. 4). The activities here include development of detailed plans, specifications, schedules, and cost estimates (supplemented with additional field work, if required) for the total construction stage that follows. Normally the responsible government agency (e.g., the Corps of Engineers for military projects) performs these activities supported by outside contractors, as required.

The process of designing a tunnel, including the excavation system, is based to a large extent on judgment and experience. There are many factors that can affect the tunnel design and cost as well as the ultimate operation, performance, and cost of the excavation system itself. Table 6 depicts the more important ones. One can broadly divide them into factors that are physical, technical, or economic and political. Physical factors include such things as the location and accessibility of the site, the geology and hydrology, the general environment including climate and altitude, and the operational requirements of the tunnel. Technical factors include geological surveying and prediction techniques and design practices. Economic or political factors include legal and organizational considerations, the availability and cost of resources throughout the time frame of the project, and the flexibility of the completion date.

How these factors might impact on the design and cost should be fairly obvious, but perhaps one example is needed to illustrate their potential magnitude. An examination of the history of a number of tunnel projects has shown that the largest single item of cost is generally direct labor. It often exceeded 50% of the total cost of a given project. Also, direct labor costs tended to increase dramatically (three-fold was the maximum observed) in urban areas as compared to rural areas. This may be attributed to such factors as higher urban wage rates coupled with the possibility of less productivity in an urban setting (congested working conditions, inexperienced workers, etc.). Clearly, the availability and cost of labor as influenced by the location of the project can have a significant impact on the cost of tunnel excavation.

TABLE 6

GENERAL FACTORS AFFECTING THE DESIGN, OPERATION, AND COST OF EXCAVATION

Physical Factors

LOCATION & ACCESSIBILITY

- Urban
- Rural

GEOLOGY & HYDROLOGY

- Rock or soil type, structure, properties
- In sity stress conditions
- Subterranean temperature
- Location & variation of phreatic surface
- General flow conditions
- Geological surveying & prediction

GENERAL ENVIRONMENT

- Climate
- Altitude

OPERATIONAL REQUIREMENTS

- Intended use (military, water conveyance)
- Operational life (permanent, temporary)
- General configuration (no. of tunnels & proximity, geometry, etc.)
- Depth, alignment, grade requirements
- Environmental control requirements (ground water, air quality, etc.)

Economic-Political Factors

AVAILABILITY & COST OF RESOURCES IN PROJECT TIME FRAME

- Labor
- Material
- Equipment
- Financing

LEGAL & ORGANIZATIONAL

- Health & safety requirements
- Union demands
- Contractual
- Management & scheduling

FLEXIBILITY OF COMPLETION DATE

- Military threat
- Impact of delays

Technical Factors

- Geological surveying & prediction techniques
- Excepted design practices

Within the framework of present-day field survey and design practices, most of the factors shown in Table 6 can be accounted for (if not explicitely, at least implicitly through the judgment and past experience of the design engineers on the project) and brought to bear on the design. Nonetheless, there is always uncertainty about the adequacy of the final design. This uncertainty can result from a number of considerations the more significant of which are:

(1) Inadequate information concerning the significant physical and economic conditions at the site. This might result from the inherent limitations of the field survey techniques used, or because insufficient time or money is devoted to the field survey.

(2) Another possible factor is the necessity to interpolate or extrapolate beyond the available data if information is lacking. This can lead to faulty projections.

(3) Finally the adequacy of present-day design practices themselves are uncertain. In many areas these practices are based on an incomplete understanding of how the many factors shown in Table 6 interact and ultimately impact on the design. Indeed, the validity of these practices is often based on opinions of key individuals--whose judgment and experience in tunneling allows them to be regarded as experts--rather than on objective scientific fact.

In the competitive bidding phase (Activity No. 4 in Fig. 4), a specific prime contractor together with his team of subcontractors prepares his own schedule and cost estimates for submission. Once the bid from each team is received, the responsible government agency compares the bids with its own predetermined schedules and cost estimates, and on the basis of the lowest qualified bidder selects the team for the construction phase.

Soon after they are selected, the prime contractor and the subcontractors will normally spend a period of time, before actual construction begins, mobilizing the necessary resources (Activity No. 5 in Fig. 4). This phase generally includes obtaining the necessary building materials, securing the labor force and equipment, and constructing temporary facilities to house field offices and auxiliary equipment such as power plants and ventilation systems.

The construction stage shown in Fig. 4 follows. It includes a primary phase (Activity No. 6) devoted to the actual tunnel excavation, and a secondary phase (Activity No. 7) devoted to additional or accessory construction related to the operation of the tunnel. The secondary phase might involve the installation of a roadbed, walkways, permanent lighting, and so forth.

The discussion up to this point illustrates the many factors that influence the physical excavation process. It should be pointed out and emphasized that the excavation simulation (discussed in Sec. IV of this report) is focused directly on Activity No. 6 in Fig. 4. In this study, no attempt was made to model directly either the preconstruction stage activities or the secondary phase construction (Activity No. 7), although the impact of these external factors was always kept in mind and considered in the design of the excavation simulation as required.

B. THE EXCAVATION PROCESS ITSELF

Figure 5 represents the general flow of activities associated with the primary construction phase of a typical tunneling project. This figure is a more detailed representation of Activity No. 6 of Fig. 4, discussed in the previous section. Although Fig. 5 looks at a more detailed level, the activities defined there are still generic. This is an attempt to define on the most general level those characteristics and logical interrelationships common to all underground tunnel excavations, and therefore basic to the nature of the excavation process itself.

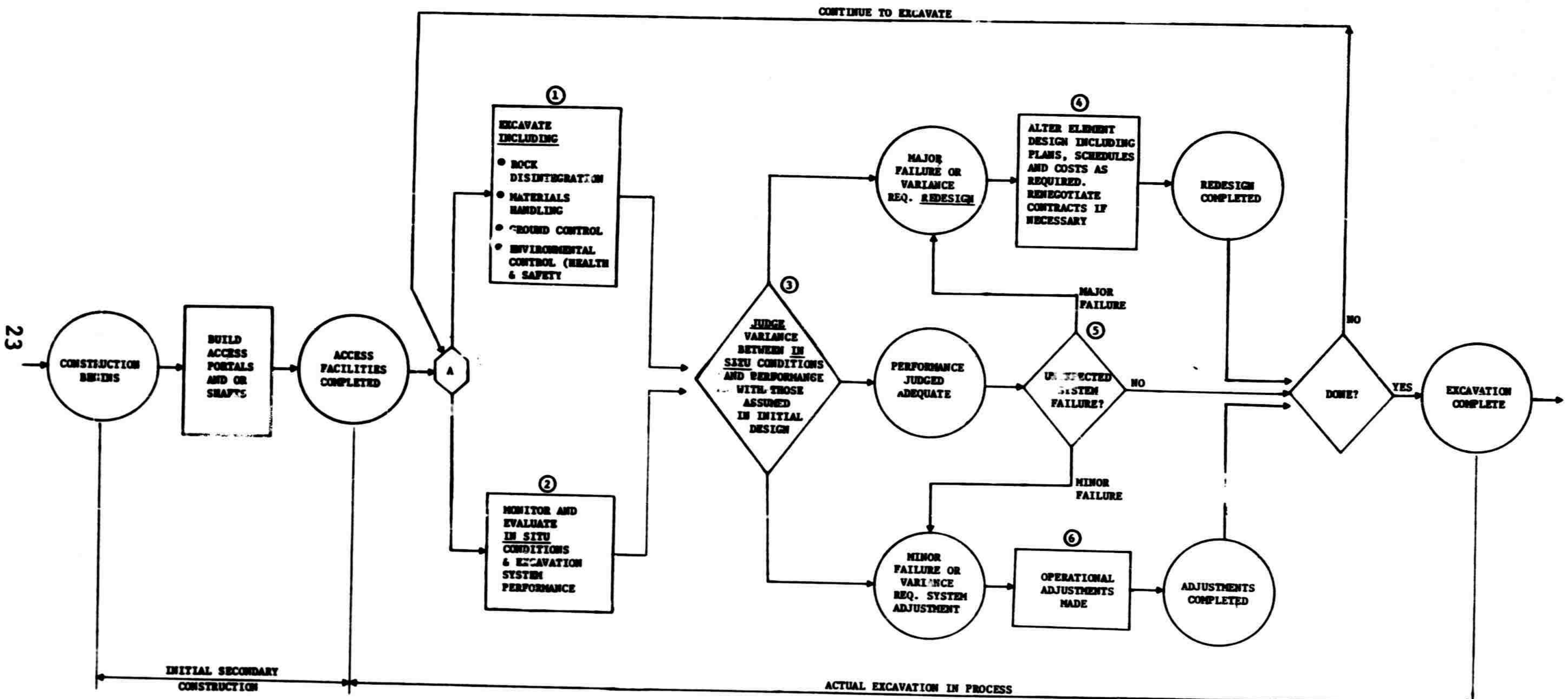


Figure 5. Direct Cost for Dual-Use Utility Tunnel Blast Shelter

Because of this, Fig. 5 is an important and useful figure for aiding the selection of those decisions to be incorporated into the model and those to be left to the user. It also provides the basic control framework for the tunnel model discussed in depth in Sec. IV. The remainder of this section is concerned exclusively with this figure.

Beginning at the left of the figure, the reader will note that construction of a tunnel normally begins with the building of the necessary access portals and/or shafts. If the project is a tunnel intended for permanent use, this activity may also include building the associated permanent facilities (at or below ground level) including administrative offices, and ventilation and power equipment facilities. In this study, it was decided not to attempt to model the building of the access facilities at this time. This aspect of the construction was considered to be of secondary importance (see Sec. II) as compared to the actual process of excavating the tunnel. The excavation simulation, which is discussed in Sec. IV, therefore begins with the point identified as Point A in Fig. 5.

At Point A, the construction contractors begin excavating under a predetermined plan to achieve an overall tunnel design. From the discussion in the previous section, recall that this design is very often based on estimates of conditions in the field that generally involve considerable uncertainty. In fact, the design itself represents at most a best estimate of what appears adequate according to the judgment and experience of the design engineers on the project (see Sec. III-A for a more detailed discussion of the design phase).

On the other hand, the construction engineers responsible for the project in the field are generally left in the precarious situation of having to deal with the uncertain consequences of a potentially inadequate design. Their normal response is to assure that the performance of the excavation system, related to the actual in situ conditions encountered,

is thoroughly monitored and evaluated concurrently with the actual excavation. This is represented in Fig. 5 by the two parallel branches just after Point A.

The general activity in the upper branch, identified as Activity No. 1, represents the actual process of excavating. As shown, this process can be broken down along functional lines into the four basic, generic elements of Rock Disintegration (breaking of the rock at the tunnel face); Materials Handling (carrying broken rock away from the face to the tunnel exit, and carrying necessary construction materials to the face); Ground Control (reinforcing or supporting the ground around the excavation as needed); and Environmental Control (control of undesirable gases, fumes, dust, heat, etc., within the excavation). The general activity in the lower branch, identified as Activity No. 2, represents the monitoring and evaluation activities (e.g., geological measurements) which are normally performed concurrently with the actual excavation.

Associated with these monitoring and evaluation activities is an implicit judgment activity (Activity No. 3) wherein the variance between the actual conditions encountered in the field and the performance of the excavation system is compared to the expected conditions and performance. This judgment can lead to one of three possible conclusions:

(1) The system performance is judged adequate in view of encountered conditions (even though it may differ significantly from expected performance), and excavation simply continues. This possibility is represented by the middle branch extending from Activity No. 3.

(2) The system performance is judged inadequate (too slow or costly, eminent failure, etc.) and requires a major redesign of one or more of the excavation system elements. In this case the total excavation process ceases and some period of time is expended in redesign and implementation activities. This possibility is represented by the upper branch extending from Activity No. 3.

(3) The overall system performance is judged <u>adequate</u> but some <u>minor operational adjustments</u> are desired to achieve better performance. In this case, the whole system, or perhaps only one or two of its elements may be shut down but only for a short period of time. This possibility is represented by the lower branch extending from Activity No. 3.

A drill-and-blast system, for example, is likely to require operational adjustments (Activity No. 6) during excavation. Various drill techniques and amounts of ground support (e.g., rock bolts at varying spacing, plus wire mesh--depending on rock quality) might be indicated by geological variations. The performance of the rock drills and the conditions for ground support would vary, depending on the geological conditions met, but the overall system itself would be as initially specified. In this case, the decision logic to be included in the model under Activity No. 3 (but which may be overridden by the user) would make the suitable selection of drill techniques or amounts of ground support according to observed conditions. This selection would be made from options defined by the user in the initial input specification of the system.

Alternatively, as an example of a major redesign effort (Activity No. 4) consider Colorado's Straight Creek Tunnel presently being constructed through the Continental Divide near Denver. The following excerpts from the April 22, 1971 edition of the <u>Engineering News Record</u> show that major redesign activities can involve considerable losses in terms of time and dollars and may even require renegotiation of contracts or the changing of contractors:

> Miners may finally win the battle they have been waging for more than three years to get the first of a pair of Interstate tunnels through the Continental Divide high above Denver.

... Since the beginning of work in 1967, conditions at the site have frustrated the designs of competent engineers, nearly driven a respectable contractor to bankruptcy, caused day-to-day changes in equipment, materials and procedure and forced almost a year's delay in tunneling. R. C. Hopper, project engineer for the state, says the basic problem is that conditions call for design at the face rather than at the drawing board. "Every design and every planned procedure has been right, according to the book. The trouble is the damned mountain can't read." he says.

... Differences of opinion on design cropped up shortly after Colorado awarded the contract to Straight Creek Contractors, Inc. ... .

... The contractor requested permission to change the cylindrical section to a modified horseshoe and mine the area with a specially designed shield, as proposed by its consultant, Setter, Leach & Linstrom, of Minneapolis. When the state accepted the proposal, SCC ordered the shield, a 22-ft-long monster weighing 650 tons with its tailpiece and capable of exerting a push of 20 million lb.

... When the $1.25 million shield arrived, it was delivered to the west heading and erected in an oversize chamber 4,100 ft from the west portal. Its rollers were set on concrete tracks cast in foundation drifts cut ahead of the main heading. The shield began working in August, 1969. After advancing only 70 ft in a month, it was determined that the rollers had failed and modification was necessary.

After several months of delay the shield was mounted on skids and started again. This time the rig moved only 7 in. before excessive pressures exerted by bad rock forced the contractor to abandon it and look for another way to penetrate the area. Today the shield, minus its working parts, is concreted into the bore as what may well be the most expensive tunnel steel ever used.

... It took almost a year to revise the tunneling method and resolve consequent financial difficulties.

In the case of major redesign (Activity No. 4), the model for Activity No. 3 will allow the user to insert a new system design during execution. The criteria for this insertion as well as the incremental time (Δt) and dollar (Δc) losses incurred because of the delay will be left as a user input. Actual simulation of redesign activities to compute Δt and Δc does not appear practical or feasible.

A final point to be noted from Fig. 5 is that even if performance is judged adequate during Activity No. 3, it is still possible for major or minor system failure and breakdown to occur (see Activity No. 5). This might be due to random causes entirely unexpected and unpredictable (e.g., derailment of a muck car, difficult and unexpected geological conditions--blocky ground or excessive shifting of rock). System breakdown might also occur because the performance evaluation during Activity No. 3 itself is faulty, reflecting either inadequate monitoring or errors in judgment.

Simulation of unexpected failures (Activity No. 5) will not be attempted at this time. Instead the decision logic will be built to allow the appropriate time delays and added costs associated with these failures to be incurred according to user specified criteria.

In summary, Fig. 5 shows that judgment in the field is an integral part of the actual excavation process, and can dramatically affect the cost and performance of the excavation system. Operational decisions such as deciding the type and amount of ground support according to varying geologic conditions appear amenable to modeling and will be incorporated into the simulation. On the other hand, the delays in time and increases in costs associated with major redesign efforts or unexpected failures will not be modeled directly but may be included as user-specified inputs.

C. GEOLOGICAL SURVEYING AND PREDICTION

1. Introduction

The previous discussion in this chapter indicated that a number of factors can have a direct or indirect effect on the ultimate performance of the excavation system. However, it is generally recognized that the geological (and hydrological) conditions more than any other factor determine the degree of difficulty and the cost of a given tunnel project. This is easy to see, since the tunneling system, support and liner design, and total system performance are a direct and strong function of the geologic medium to be tunneled through. In essence, the latter is truly the key variable in the total economic picture of a project. As a result, geologic exploration and prediction techniques have a very important influence on the planning, design, and performance of an excavation system. In this section we shall review the general objectives and related problems of geological surveying and prediction, discuss current and possible future measurement techniques and procedures, and identify the interactions between geological conditions and other portions of the excavation process that bear directly on the modeling and simulation of the excavation system.

2. Overview of the Problem

Traditionally, geological surveying, measurements, and prediction are accomplished before any detailed designs and cost estimates are attempted. The sum total of such procedures is represented as Activity No. 2 in Fig. 4. Although geophysical measurements are sometimes made during the course of the excavation process, the current practice is to perform essentially all of the geological work prior to excavation.

Depending upon the extent of the geological survey and measurement program, the information and data that it evokes might be used in site selection and feasibility determination, preliminary design and cost estimates, or detailed construction planning. However, as a result of

both the coarse nature of geological measurements and the cost of detailed exploration programs, such decisions and studies are almost always based on incomplete information. Consequently, engineering judgment tempered by previous experience plays a significant role in the decision processes. We shall have more to say about this later on, but given that the site, geometry, and orientation of a tunnel project has been chosen, we can focus attention on the fundamental data requirements imposed upon the engineering geologist.

The results of a geological exploration program should consist of sufficient amounts of data concerning lithological, hydrological, and rock-mass properties to enable a designer and contractor to plan a construction project with confidence. This includes both the quantitative aspects of engineering and excavation system design, and scheduling plans and cost estimates. In other words, the contractor wants answers to the following key questions:

1. What would be the most suitable excavation method?
2. What are the ground support and tunnel liner requirements along the length of a proposed tunnel?
3. How much ground-water inflow can be expected along the tunnel length?
4. What is the location of potential geologic hazards?

The extent to which such questions can be answered with precision and reliability determines to a large extent the ultimate cost-performance success of the construction project.

3. Current Geological Surveying and Measurement Techniques

In this section we shall present a brief survey of those measurement techniques and procedures that are now in general use for geological surveying and prediction. Since comprehensive discussions along these

lines are readily available in the literature,[11-16] we shall focus our attention primarily on the extent to which these various techniques are able to delineate geological discontinuities and inhomogeneities such as faults, joints, bedding planes, rock-soil interfaces, and ground-water concentrations. In addition, we shall present relevant cost data, and discuss the technical and economic factors which influence the scope of a typical geological exploration program.

A comprehensive geological exploration program typically involves the following kinds of activities:

- Review of available data (literature research)
- Surface exploration and mapping
- Subsurface studies
- Laboratory analysis of field samples

The degree to which efforts are directed in each area depends not only on technical and engineering considerations but also on economic factors and judgment. This will be elaborated below.

a. Literature Review

An exploration program generally begins with a survey of available literature dealing with geological and engineering geological information pertaining to the area of interest. The objective is not only to save time and expense but also to utilize the information to plan the remaining elements of the exploration program more efficiently and effectively. Of particular interest is information relating to the spatial distributions of rock formations along the tunnel route, the physical properties and quality of the rock types that might be encountered at depth, and expected or possible ground-water conditions during excavation. If underground construction data for previous projects in the general area are available, they would most likely be used to assess the structural characteristics of the geological strata, and possible problem areas. The sum total of

such sources of information would be expected to aid the geologist in interpreting conditions with respect to possible problem areas, tunnel support requirements, and ground-water conditions. Of course, the amount of useful data that can be gathered depends on the extent of previous surface and underground construction in the general vicinity of the proposed tunnel.

b. Surface Exploration

Surface investigations comprise the second step in the sequence of progressively refined studies and measurements. With the exception of built-up urban areas, most geographical settings are suitable for surface geological exploration. The objective of this phase of the program is to survey and map in detail the exposed rock formations in a wide area covering the contemplated excavation. The usefulness of this procedure depends on the degree to which geological formations and structures of interest are exposed at the surface. In some cases, aerial and surface reconnaissance is aided where necessary by bulldozer stripping of surface soil to expose underlying rock formations. This is usually an inexpensive way[11] to implement the surface work.

The results of this phase of geological exploration are recorded on a topographical map of the type made available by the U.S. Geological Survey. The map scale may vary between 1200:1 and 4800:1 and the following geological features are usually displayed:

- General geology (location and classification of generic rock types)
- Strike and dip of surface outcrops
- Location of fault zones and veins
- Description of foliation and joints
- Fracture densities as a function of location
- Degree of weathering

When the information is displayed in this form, it is useful to the geologist in connection with two main tasks: it serves as the basis for making a preliminary extrapolation of rock conditions to tunnel depth, and it aids in the planning of subsequent geological and geophysical measurements, such as core drillings and seismic surveys. It is worth while to emphasize that at this point the geologist cannot predict with a high degree of certainty what geological factors will be encountered at depth. The information, when evaluated and interpreted by an experienced geologist (and we must emphasize interpret) serves as a basis for perhaps semiquantitative estimates of expected conditions. Conditions are rarely predicted easily since much of the earth's outer crust consists of highly variable geological structures and conditions. Therefore, to increase the information usable for design purposes, additional measurements and tests are often planned, as a result of questions raised by the results of the surface geological mapping. Occasionally, field samples are collected during the surface survey for laboratory analyses and identification.

c. Subsurface Investigations

As discussed in the previous sections, the geologist's chief goal is to measure and/or predict the geological conditions at the depth of interest. It is usually necessary to refine the data obtained from surface mapping by detailed investigations of areas of known faults, areas of potential geological problems, and ground-water conditions. Toward this end, a number of procedures and measurements are currently in use:

- Core drilling
- In situ pilot bore
- Field geophysical measurements

The second method is still in the research stage since an adequate procedure to measure and monitor geological characteristics in the hole has not yet been developed.

Core Drilling: Information concerning subsurface conditions is obtainable by drilling small vertical (or nearly vertical) holes down to tunnel depth, with the concommitant examination and testing of the removed material (core samples). Holes drilled in rock are usually about 3 inches in diameter, and the amount of core recovered is a function of the quality of the rock and the skill of the drillers. Data on rock properties and geological conditions as a function of depth are obtained through core logging, water testing, and laboratory measurements of core samples.

Core Logging: This is essentially the systematic recording of observations of rock properties for successive core samples. In particular, parameters such as rock type, fracture and joint spacing and orientation, density, and hardness are of immediate interest. Since heavy ground-water conditions are particularly influential in a tunneling operation, data on changes in the water level encountered, as well as porosity and permeability measurements and pumping tests, are of value.

In Situ Pilot Bore: In view of the inherent deficiencies in the techniques discussed above, the need for exploratory drilling ahead of a working face has been widely recognized.[17] Current geological investigation techniques do not provide enough information for design purposes, nor are they capable of being applied simultaneously with the excavation process. As a result, it would be desirable to obtain in situ geological information in advance of a working face. Some isolated attempts have been made to drill a small probe hole ahead of the excavation and examine the recovered core for potential bed ground conditions. However, further research still needs to be done to provide a satisfactory instrument package usable with a pilot drill.

A variation of this concept has also been tried; a complete pilot tunnel has been excavated in the immediate vicinity of the intended tunnel. The traight Creek Tunnel Pilot Bore is an example of this procedure. A small pilot tunnel was excavated and subsequently surveyed by geophysical techniques. The resulting data indicated potential trouble spots, and some correlation of rock properties with construction parameters was made. If such a procedure could be made more economical, it would represent a very effective geological measurement tool.

Field Geophysical Measurements: In addition to the techniques mentioned above, surface measurements are occasionally made using seismic velocities as indicators of intrinsic rock properties and changing geological conditions. However, its effectiveness is frequently limited by insensitivities of the techniques used and by an inability to distinguish clearly between certain kinds of rock. Surface measurements of DC electrical resistivity have also been used to detect changing rock and groundwater conditions, but with modest success. However, data from the Straight Creek Tunnel Pilot Bore[15,16] indicate that such measurements may be of definite value in conjunction with other in situ techniques.

In addition to logging techniques, some use has been made of borehole photography to provide direct observation of geological conditions inside the borehole. Finally, geophysical measurements of seismic velocities in boreholes are also performed. Depending on the physical differences among the rock types encountered, such data can be used to correlate other surface geophysical measurements. Unfortunately, unless the boreholes are spaced close enough along a proposed tunnel route to reveal all geological changes bearing on engineering design and construction, the resulting information is only generally indicative of conditions to be expected. Core logs are often incapable of indicating the extent of geological discontinuities. As a result, the data yield only an incomplete picture of geological and hydrological conditions at tunnel depth. However, in mining operations core boring techniques may provide all the useful information that is needed.[18]

d. Laboratory Tests

In addition to the logging and measurement techniques used in conjunction with core boring, laboratory tests are usually performed on the intact core samples. The object of such tests is to determine those rock properties which influence the excavation method, support and liner design, and probable ground-water conditions. In particular, such parameters as unconfined compressive strength, hardness, fracture and joint spacing, and degree of weathering are of immediate interest. Prospective bidders and/or tunnel machine designers might perform additional tests of their own choosing to enable them to evaluate the relative advantage of drill and blast versus machine tunneling, but such tests are performed after the initial geologic investigation is made. In recent years, the rock quality designation (RQD)[14,19,20] has come into use as a simply measured indicator of overall rock quality. It is defined as the fraction of the recovered core pieces with a length greater than or equal to 4 inches. Thus, it is an approximate measure of the influence of discontinuities on the rock mass encountered. This will be discussed in more detail in a subsequent section, but it suffices to say at this point that the RQD can be correlated at least partially with engineering and construction aspects of tunneling. At the present time, laboratory measurements of intrinsic rock properties are useful only in furnishing guidelines for support design purposes. The measurements are useful, but enough uncertainty remains to require the use of large safety factors in design and construction.

Cost Data and Economic Considerations: Generally speaking, the two most important parameters characterizing the construction of a given tunnel are the total cost and the average rate of advance. As mentioned previously, the geological and hydrological conditions are the chief independent factors in determining the overall project cost. However, less than 1% of the total project cost is generally allocated to pre-excavation geological investigations.[21,22] This probably reflects the fact that the scope and extent of the geological survey is a compromise between technical

desirability and economic feasibility. Moreover, the point of compromise may not be reached objectively in many instances. Budgetary considerations of sponsoring agencies, political considerations, etc., may also play a role in the decision process. As a result, one cannot readily provide general rules which determine the optimum spacing between drill holes as a function of such parameters as tunnel length and geology. The range can be anywhere from a few hundred to a few thousand feet. However, Table 7 summarizes typical costs associated with geological surveying and measurement procedures. They can be used to estimate the total cost of postulated exploration programs.

TABLE 7

COST ELEMENT OF GEOLOGICAL SURVEYING

Item		Typical Costs
1.	Core drilling into bedrock (3-in. diameter) with boxing of cores	\$5-\$25/ft
2.	Water pressure tests	\$75/test
3.	Mobilization/demobilization (per drill rig and crew)	Variable (several hundred to several thousand dollars)
4.	Observation well (1 1/2-in. diameter)	\$4/ft
5.	Surface mapping	\$100/(day-geologist)
6.	Literature research	\$2100/man-mo. (office)
7.	Laboratory tests	\$25-\$100/sample
8.	Seismic tests (surface)	< \$1/lin. ft

It should be mentioned that the cost per foot of core drilling depends somewhat on the diameter and ultimate depth of the hole. Thus it can be seen that drill holes of 500-foot depth might typically cost $5,000 or more each. This explains why their locations are chosen with care. Finally, it should be mentioned that in situ engineering tests for design purposes are usually more costly and time consuming than laboratory tests. This includes, in particular, radial jacking tests to measure the deformation of tunnel wall rock under various loading conditions.

4. Current Research Programs

In this section we shall review the objectives of current ARPA-sponsored research in the area of geological measurement and prediction. Emphasis will be placed on those techniques that can be used in situ in conjunction with a boring machine. The nature and direction of the overall research program has been in large part on research needs that were identified in 1966 by a special panel of the Committee on Rapid Excavation under the auspices of the National Academy of Sciences - National Academy of Engineering.[17] We shall review these objectives with a view toward assessing their implications for rapid excavation technology. Table 8 summarizes the present contractors and their research areas.

Bendix: Thermal Monitoring

The basic goal of the program is to determine the feasibility of using measurements of the temperature distribution along the walls of an excavation as an indicator of potential hazards during a tunneling operation. In particular, information is sought concerning the degree of rock consolidation, the presence of nearby moving ground water, and gas seepage. The approach will involve both theoretical modeling of expected temperature distributions and the design, fabrication, and testing of suitable measuring instrument (radiometer).

TABLE 8

PRESENT ARPA PROGRAM ON GEOLOGICAL MEASUREMENT AND PREDICTION*

Contractor	Research Project
Bendix Research Laboratories	Thermal monitoring of geological changes during excavation
Bendix Research Laboratories	Seismic and acoustic determination of geological discontinuities
Honeywell Research, Inc.	Excavation seismology
Jacobs Associates	Long-hole exploratory drilling concurrent with machine tunneling
Ohio State University	Electromagnetic pulse reflection
University of Michigan	Tunnel site selection using remote sensing techniques

*Information provided by U.S. Bureau of Mines personnel.

Bendix: Seismic and Acoustic Measurements

This research study is concerned with the feasibility of using ultrasonic and seismic reflection techniques to locate the presence of large geological discontinuities (such as an old mine working) filled with water or gas. Potential sources, detectors, and operating parameters will be investigated, and ultimately acoustic reflection data will be generated using the most promising system(s) concepts.

Honeywell: Excavation Seismology

The goal of this research project is to conduct a series of field experiments to study the effectiveness of the signal-enhancement or stacking method for underground seismic mapping. Essentially, this

involves applying ideas that have already been used with radar and sonar signal processing to the excavation setting. Reflected seismic signals are detected by an array of seismometers, and their outputs are summed electronically to produce a usable signal. Efforts will be devoted to conducting a complete system analysis and trade-off study involving source and receiver characteristics and operational parameters.

Jacobs Associates: In Situ Exploratory Drilling

This is essentially the first systematic effort devoted to the design and testing of a prototype drill capable of determining geological conditions and rock properties in advance of tunnel boring machines. It is intended that the drill be capable of operating in conjunction with mechanical tunneling machines, with minimal interference with the overall operation. Moreover, the desired performance in hard rock is such that the drill would lead the tunneling operation by several days.

Ohio State University: Electromagnetic Pulse Reflection

The goal of this research project is to investigate the feasibility of using electromagnetic pulse sounding techniques underground to detect the presence of water-bearing faults or shear zones, or man-made holes and shafts. Again, the intention is to obtain a geophysical technique capable of providing information on geological conditions ahead of a working face. A combined theoretical and experimental approach is being taken.

University of Michigan: Remote Sensing Techniques

An airborne measurement system consisting of microwave radar, infrared scanning (0.3-13.5 μm) and aerial photographic equipment will be designed and tested for possible use in tunnel site selection. The data will be analyzed, and the usefulness of the techniques will be evaluated from the standpoint of their effectiveness in delineating surface and subsurface geological conditions.

Discussion

The benefits that might accrue from positive results of the research programs described above can best be evaluated by examining the overall needs of rapid excavation technology. It has been recognized that to bring about significantly higher sustained rates of advance and lower project costs, improvements are needed in several areas: geological prediction, rock fragmentation, tunnel support installation efficiency, and materials handling. Considering geological prediction, we can see that there is much to be gained by achieving one or more of the following objectives: decrease the cost of core drilling, develop an in situ pilot bore drill, increase the quality of the data obtained by current geophysical measurements for use in situ. No matter how it is accomplished, an improved knowledge of geological conditions (either during or before excavation), or better still, an adequate knowledge, will improve current excavation systems with respect to cost and performance. Delays or even temporary shutdowns frequently result when unexpected, troublesome geological conditions are encountered. By eliminating such events, one could realize large savings in time and money. Similarly, an adequate knowledge of geological and hydrological conditions would permit more efficient planning, scheduling, and utilization of labor and materiel. We should emphasize that this could possibly include savings resulting from decreased tunnel support requirements due to improved knowledge of rock properties and lithology. The following excerpts, taken from a recent article[23] in the Engineering News Record, typify the kind of situation that the above research is directed toward:

> ... Apparently, no one anticipated any real difficulty in getting through, but troubles started early in the job.... The seriousness of the condition became obvious ... when a 24-ft high overbreak appeared in the tunnel roof after a light round was fired. The tunnelers spent the next two weeks worrying their way through 60 ft of badly decomposed shale. The conditions worsened and on Jan. 11, 1969, Langfelder ordered a halt to the tunnel work. For the next five months the contractor,

highway department and ... the engineers who designed the tunnel discussed both the engineering and economic aspects of the work.

In reviewing the geology research programs, it is evident that an economical and effective pilot bore drill, capable of operating in conjunction with drill-and-blast or machine modes of excavation, offers a potentially high payoff in terms of eliminating or reducing such situations. Moreover, if geophysical techniques can be developed to serve the same function, then all of them should be evaluated and compared on the basis of cost effectiveness. But it is also clear that ultimately the best solution to this problem is to obtain advance warning of bad geology during the pre-excavation phase of construction. This would provide greater flexibility in site selection and more efficient planning of subsequent construction. From the point of view of research priorities, therefore, the realities of the problem suggest that significant continued emphasis be placed on investigating refinements and improvements in present day core drilling and surface geophysical studies. To develop a precise measurement tool, extensive field tests will be necessary to correlate such geophysical measurements with known rock structures and defects.

5. Influence of Geology on Excavation Elements

From a systems analysis viewpoint, the interaction of geological and hydrological conditions with other elements of the excavation process must be clearly delineated in order to develop an accurate simulation of the entire process. The physical and structural characteristics of a rock mass and the associated ground-water conditions influence strongly the rock fragmentation technique and the required tunnel support and liner system. To a lesser extent, one can identify some influence of geology on the materials handling and environmental control aspects of tunneling. We shall briefly discuss in general terms below the nature of these interactions; the specific details required for the computer simulation will be discussed in Sec. IV.

Geology - Rock Fragmentation Interaction

The effectiveness of rock fragmentation processes depends directly on the intrinsic and structural properties of the rock mass. The functional dependence may not be as strong in the former case as it is in the latter, but nevertheless current techniques do rely explicitly on knowledge of geological conditions. In the case of a boring machine, both cutter design and overall machine performance are strongly influenced by rock mass parameters such as compressive strength and hardness. Although there is no generally acknowledged analytical relationship between rock parameters and "drillability," machine designers have been successful in developing machines that are effective in rocks of increasing compressive strength. The current upper limit in compressive strength for machine effectiveness is about 20,000 psi. Attempts have been made with some success to correlate rock fragmentation by drill-and-blast (D&B) or machine with overall rock quality (RQD). Much work remains to be done along these lines, but general trends have been established. One can probably say that there exists at least some understanding of the dependence of boring machine and D&B performance on such parameters as hardness, compressive strength, and fracture spacing.

Geology - Tunnel Support Interaction

The design of a tunnel support system is based on the measured or assumed rock loads surrounding an underground opening that are not supported through natural arching action. Depending on the competence of the rock mass, one can distinguish between tunnel reinforcement and direct support. In either case, the residual stresses in the rock mass, as well as the fracture and joint spacing, the allowable deformation of the tunnel liner, the expected water pressure, and the effects of the rock fragmentation process all directly influence the amount of tunnel support required during construction.

Geology - Environmental Control Interaction

This interaction is significant to the extent that hazardous geology (extensive fault zones and badly weathered rock) and/or large ground-water inflows are encountered during a tunneling operation. Since health and safety considerations are particularly important in such situations, the interaction is quite evident. The ground-water inflow determines the need for, and the extent of pumping, grouting, or drainage. In addition, air conditioning and ventilation requirements are a direct function of the depth of a tunnel, since underground temperatures tend to increase with depth.

Geology - Materials Handling Interaction

To the extent that ground-water inflows interfere with the materials handling process, one can identify an interaction leading to a reduced performance or efficiency. This is probably a very small effect in general; its inclusion in a computer simulation is, therefore, not of immediate concern. The effects of the size, abrasiveness, or angular projections of broken rock on conveyor belts might influence the choice of the materials handling system; this, however, is also not included in the simulation.

IV. THE EXCAVATION SIMULATION

A. DESIGN CONCEPTS OF THE EXCAVATION MODEL

Section III emphasizes that the excavation portion of the underground construction effort is the primary concern of this study. Excavation consists of several interrelated elements (rock disintegration, materials handling, ground support, environmental control, etc.). Each of these may utilize any of several general processes (rock may be disintegrated by boring or by drilling and blasting, for example) consisting of several activities (drilling and blasting, e.g., comprise drilling holes, setting charges, and shooting), which in turn can employ any of several techniques (jackleg drilling or drilling by drifter drills mounted on a jumbo, etc.). If one could simulate such a branching structure, one could then select and coordinate to formulate comprehensive excavation systems. This is the basic philosophy that is followed in designing the excavation model, and the selection process will require care and judgment. (Of course, it is really not simple since not all activities are compatible, and some techniques are not yet well enough understood to be realistically modeled.)

The following terminology and definitions summarize the basic classification scheme discussed above:

(1) EXCAVATION. That portion of the total effort of constructing a hard rock tunnel which directly and physically contributes to the removal of the rock and the preparation of the resulting empty space for use as a tunnel.

(2) ELEMENT. Functional breakdown of the overall excavation effort at the most general level. This normally includes:

- Rock Disintegration. Breaking the rock at the tunnel face.
- Materials Handling. Carrying broken rock (muck) away from the face, or construction materials to the face.

- Ground Control. Reinforcing or supporting the ground around the excavation and installing permanent lining.
- Environmental Control. Control of undesirable gases, fumes, dust, water, heat, etc., within the excavation.

(3) GENERAL PROCESS. A general process is a way in which the function of a particular element of the excavation process might be performed. It is the next level of detail within a given element. For example the element rock disintegration might be accomplished by the general process of drill and blast, boring machine, or water jet erosion.

(4) ACTIVITY. Activities are those operations included within the performance of a specific general process. For example, the general-process boring machine includes the activities repositioning, boring, cutter changing, etc.

(5) TECHNIQUE. A technique is a manner in which a specific activity might be accomplished. For example the activity drilling might be accomplished by a jackleg drill technique or perhaps by drifter drills on a jumbo.

Each of the activities involved is simulated by a family of alternative subroutines, which are coordinated in order to simulate the general processes used in a particular excavation system design. It is possible to simulate alternative excavation systems by exchanging subroutines or by coordinating them in different manners, without the need for extensive reprogramming.

Note that this logical arrangement of subroutines does not require that information be exchanged only "up and down the branches" of the tree structure. If a common information exchange area is provided, it is possible for one activity to influence another even though they are not in the same general process structure. For example, rock disintegration

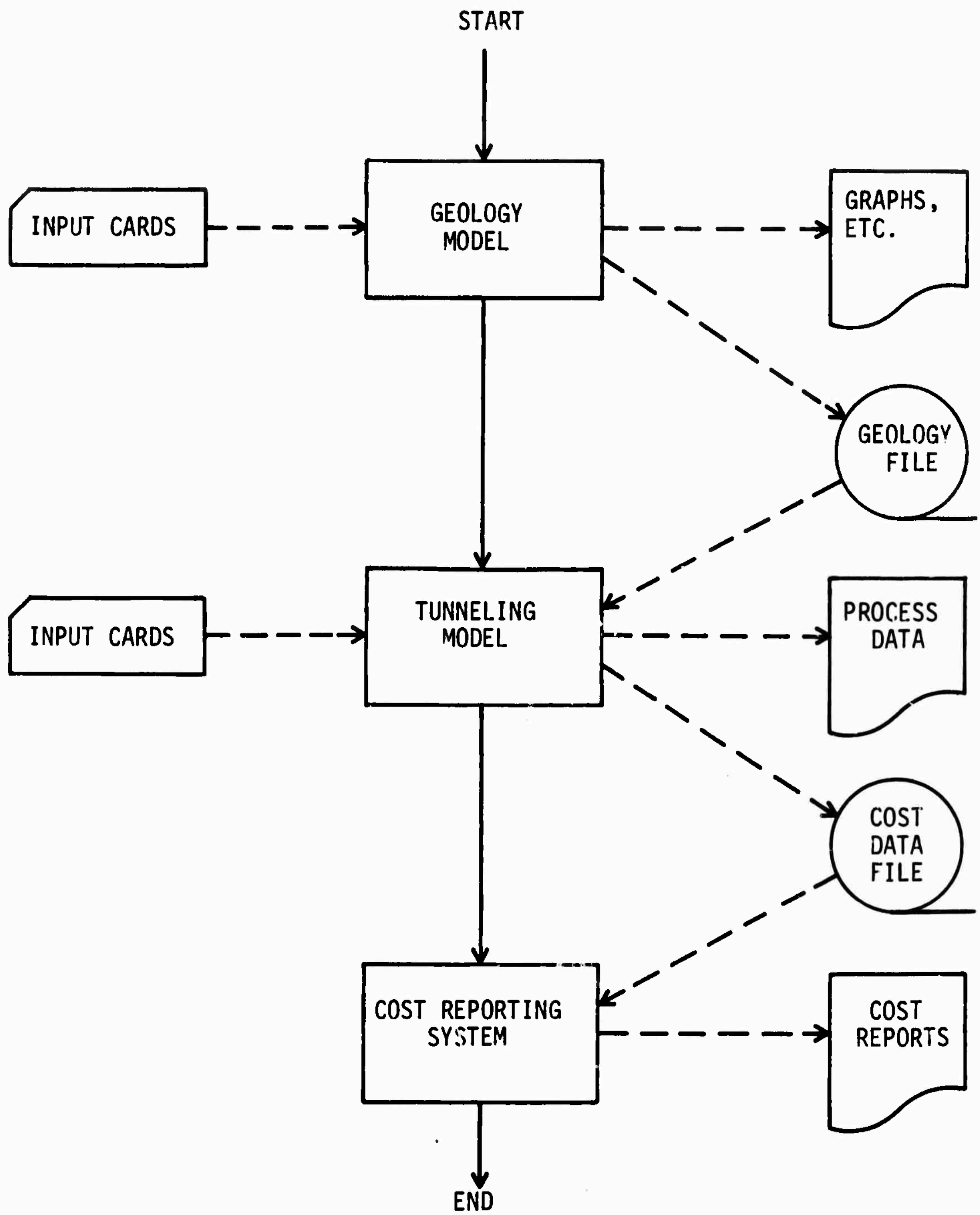


Figure 6. Excavation Model

by laser or water jet might lead to the presence of large amounts of heat or water in the tunnel, which would then have to be removed by the general processes used for environmental control. The ability to model large numbers of interactions of this kind is considered to be one of the advantages of using a computer to simulate the excavation effort.

B. BASIC STRUCTURE OF THE MODEL

1. Overview

The basic structure of the excavation model is shown in Fig. 6. The dashed lines indicate the flow of information; the solid lines indicate the sequence in which processing takes place. (This convention will apply throughout this section of the report.) There are three separate parts of the excavation model which are executed serially.

The geology model is used to produce detailed and consistent representations of realistically complex geologies, in a convenient manner. It is intended to be flexible enough so that it can be used to produce reasonable approximations of known geologies. It accepts input cards which specify rock properties by strata, buckling, faults, ground-water conditions, and so forth. It produces a geology file of a given region and miscellaneous output reports. The geology file is reusable.

The tunneling model is that part of the model which we have been referring to as the excavation model. The latter term will henceforth be used for the overall model, including the geology model, the tunneling model, and the cost reporting system.

The tunneling model is used to simulate any one of many excavation methods, including interactions with the geology of the region and interactions among the various activities involved. It accepts information from both the geology file and from input cards, which specify the coordinates of the desired tunnel and control information required by the

particular excavation method used. The output of the tunneling model consists of reports concerning the operation and progress of the tunneling simulation, as well as a file of cost information.

The cost reporting system processes the information contained in the cost information file, organizing and consolidating this information into standardized cost reports.

2. Geology Model

The most basic requirement set forth for the geology model was that it allows for the simulation of realistically complex geologies. Specifically, it was not considered to be sufficient to model the rock as a homogeneous medium. Since tunnel geometry in general has important effects on the speed and cost of tunnel excavation, a three-dimensional geology model was considered to be desirable. Simulating a changing geology in three dimensions seemed to be best accomplished in a deterministic manner, since this made it easier to ensure that geological features were encountered in realisitic sequences and contexts. Simulation of pre-excavation stresses and strains in the rock were assumed to be simulated only in a very elementary fashion, if at all, since accurate simulation of these factors would presumably require very large amounts of computer time.

The geology model has, therefore, been developed as a deterministic model of appropriate three-dimensional geologic characteristics other than pre-excavation stresses and strains. The model is designed to simulate the tectonic warping of strata having arbitrarily defined hardness, porosities, and so forth. It is intended that the model be used primarily to simulate exemplary geologies, although an effort has been made to make the model flexible enough to allow a reasonable simulation of a given actual geological region.

Basically, there are two methods of modeling the geology: serial and parallel. One can completely model the geology first, and then model the excavation process, or one can "make up" the geology as the excavation process takes place. The former approach was chosen. By modeling the geology first, we can completely separate the geology modeling logic from the excavation modeling logic; this simplifies both, and also simplifies the work involved in simulating alternative excavation methods. This approach also simplifies the work involved in evaluating the use of alternative excavation systems in the same geological conditions. In this case, the geology need only be simulated once. It can then be kept "on file" and be used repetitively by simulations of various excavation systems. The serial approach simplifies the work involved in simulating the actual geology in which one might be interested. It also simplifies the problems involved in ensuring that geological features are encountered in realistic sequences and contexts.

Using the serial approach, the geology is entirely determined before the excavation begins. This fact need not restrict the tunneling model. The tunneling model accesses the geology file to determine what the geology of a given location is, <u>only</u> when the excavation has proceeded to that point, and updates the previous knowledge of the geology at that time. From the point of view of the excavation simulation, the situation is exactly analogous to that found in actual practice; the geology is completely determined beforehand, but those who are excavating do not know for sure what the geology will be until they encounter it. The excavation simulation can therefore be made to respond to unexpected geologies in a realistic manner--involving alternative processes and techniques, time delays and added costs.

The basic structure of the geology model is shown in Fig. 7. In specifying the geology for a given region, the user first specifies the size of the region in which he is interested and the spacing desired between data points in the north-south and in the east-west direction.

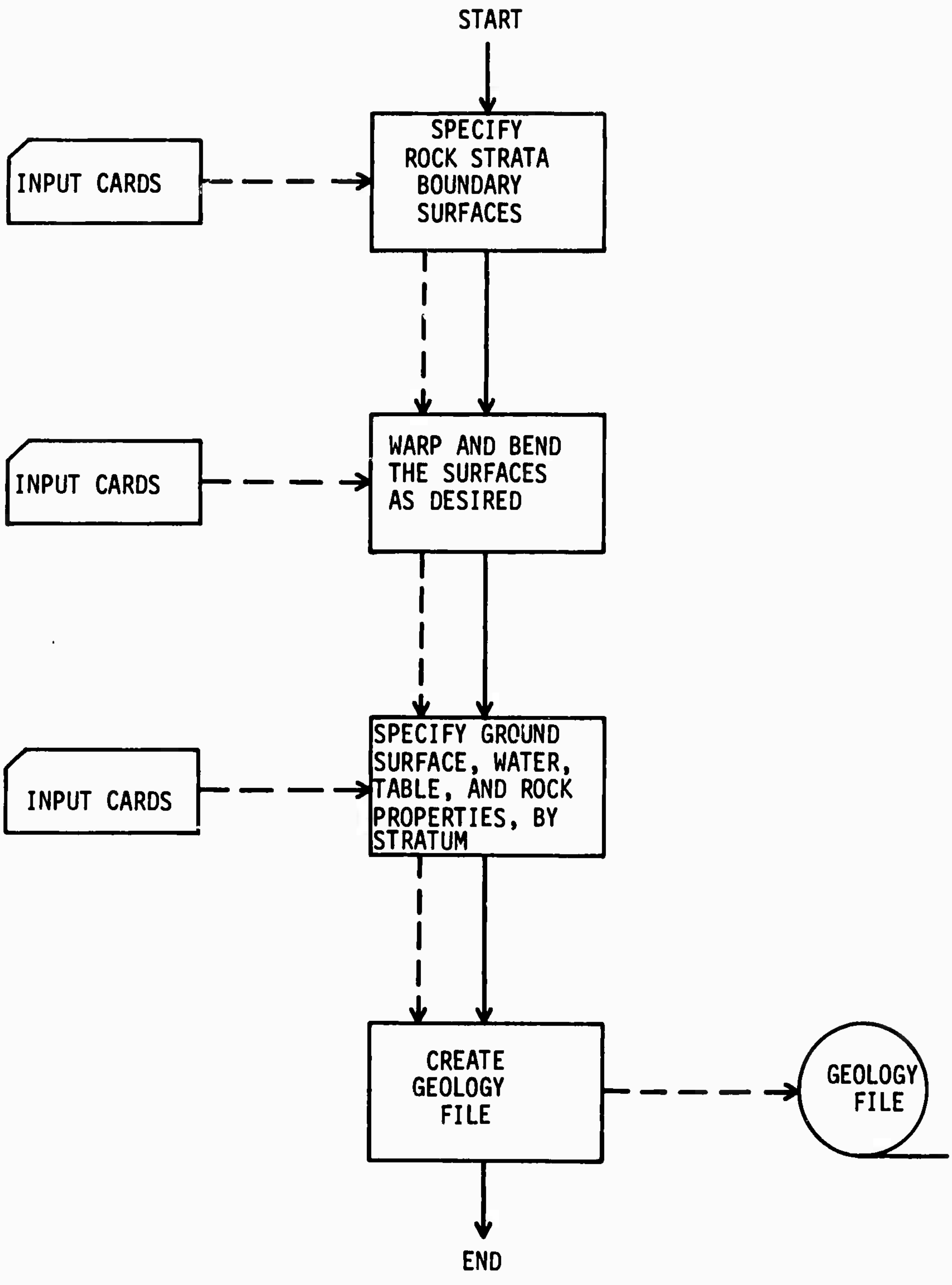


Figure 7. Geology Model

This operation is so simple that it is not included in Fig. 7, but is noted here for the sake of completeness.

The user then specifies the surfaces which form the interface boundaries of the rock strata in the area of interest. If desired, a surface can be read in, point by point, thus assuring complete flexibility of choice. Provision is also made for allowing the user to specify only the N-S and E-W boundary points; the model then solves Laplace's equation in two dimensions in order to fill in the interior points with values corresponding to the surface that an infinitely flexible membrane (e.g., a soap bubble) would assume if stretched over the boundary points. Plane surfaces can be read in with one card. Note that all of these operations take place one surface at a time.

The surfaces are then warped, bent, or faulted as required. This procedure will be described in some detail below. The main purpose of this operation is to allow the user to deform surfaces in a reasonable and consistent manner.

After the surfaces are in the desired configuration, one of them is specified as the ground surface and one can be specified as the water table. The properties of the rock between the other surfaces are specified stratum by stratum.

At this point in the processing, the surfaces are still stored individually. That is, all of the data points for each individual surface are stored together. For the geology file to be used in the tunneling model, it is desired that the information for all surfaces be stored in order by increasing depth, in a file that is indexed according to N-S and E-W coordinates. Thus, the information must be converted from data-point-within-surface order to surface-within-data-point order, as part of the effort involved in building the geology file.

The basic coordinate system used is illustrated in Fig. 8. For the sake of clarity, only one surface has been drawn.

An algorithm has been devised which produces realistic and consistent deformations of rather arbitrary surfaces. This algorithm is used as a means of simulating tectonic warping of strata. Figure 9 is an attempt to depict the kind of deformation which results when using this algorithm. This figure is portrayed in two dimensions for clarity, although the algorithm used is designed to work in three dimensions. The deformation which occurs is defined by specifying the median surface of the rock, before and after bending. (The median surface is that surface which is neither compressed nor stretched during the bending.) Other planes are deformed by the algorithm according to their position relative to the old and new median planes. Although the surfaces which are to be deformed are actually deformed one at a time, the end result is the same as if they were all deformed at the same time in a consistent manner.

In summary, the operation of the geology model involves specifying rock strata ground level, and water table surfaces, specifying rock properties by stratum, deforming the surfaces as required, and then reordering the information to produce a geology file which can be accessed by geographical coordinates. The object is to model realistically complex geologies in three dimensions, in a reasonable manner, without a great expenditure of computer time.

3. Tunneling Model

The first step in the operation of the tunneling model is to read the specifications defining the coordinates of the tunnel to be excavated, and to use this information to access the complete geology file which was produced by the geology model, in order to produce a much smaller file of geological information along the length of the tunnel. This step is performed primarily as a matter of processing convenience; the resulting reduction in the volume of the geology file and the ordering of the data

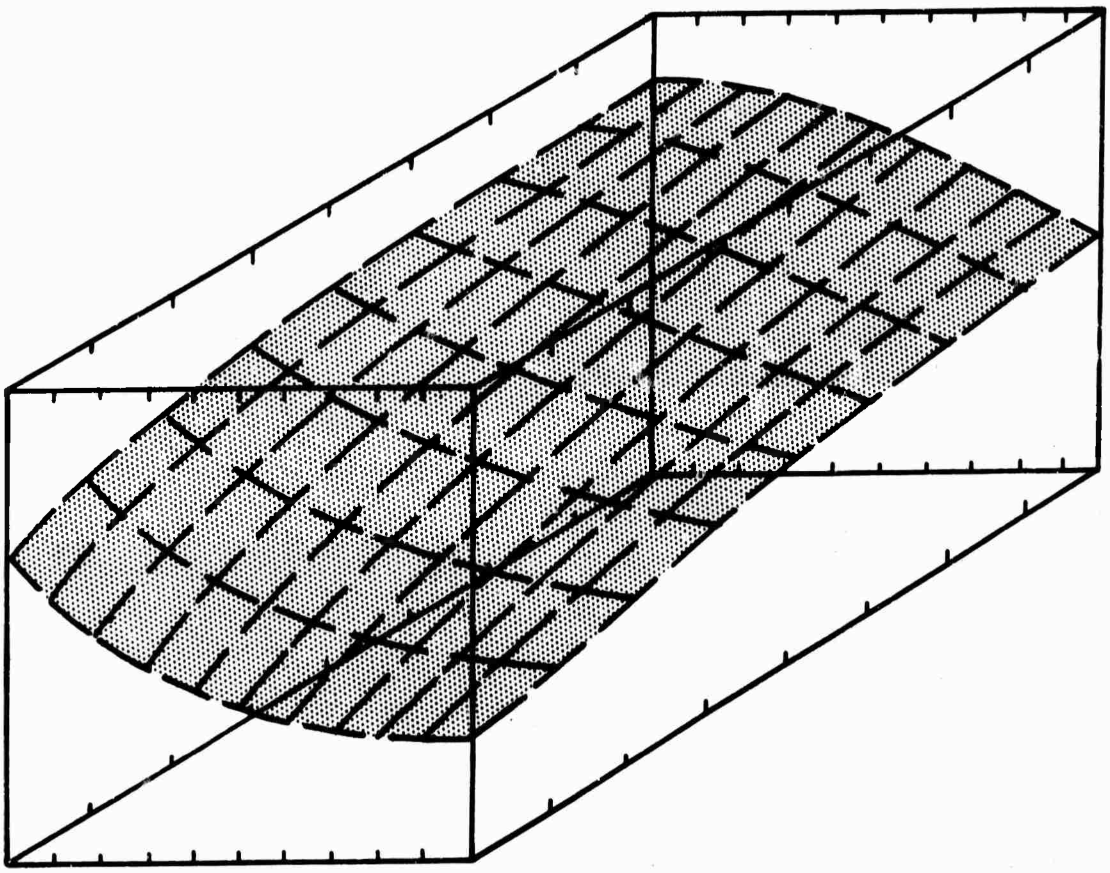


Figure 8. Representation of Geology

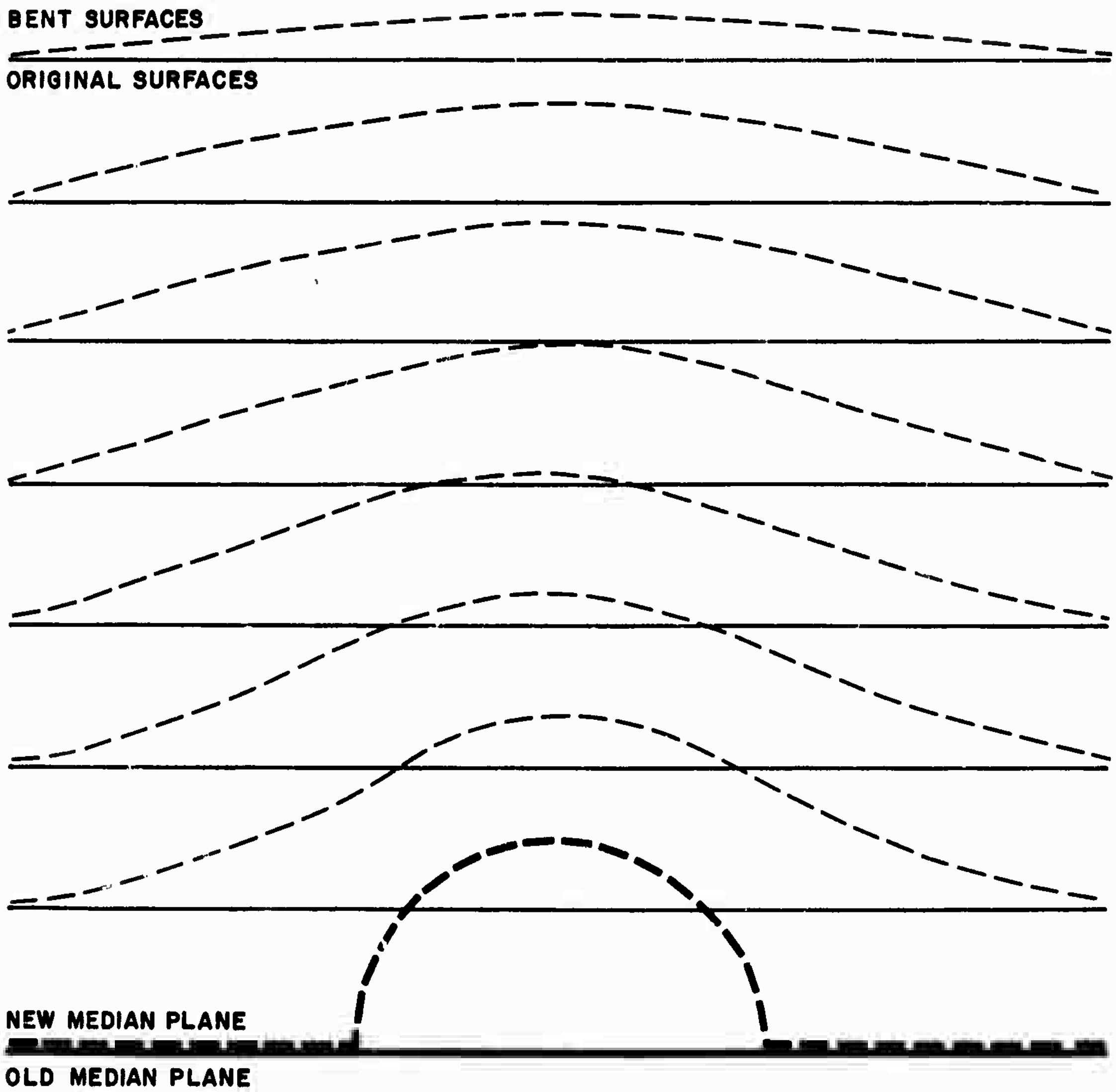


Figure 9. Bending of Rock Strata

during this operation led to the simplicification of the logic of the rest of the tunneling model. In addition, this smaller geology file provides a convenient starting point for the operation of the model during studies of the excavation of the same tunnel by alternative systems. In such studies, all processing up to this point need be performed only once. Figure 10 depicts the process of generating the file of tunnel geology versus tunnel length.

The external information flow of the main part of the tunneling model is shown in Fig. 11. The inputs to the tunneling model consist of the file of geological information versus tunnel length and input cards containing various control parameters appropriate for the excavation method being simulated. The geology file is read as the excavation simulation takes place, thus revealing a given part of the tunnel geology to the simulation program only as the corresponding position in the tunnel has been reached.

The control parameter cards are to be set up with implied default options wherever possible. As an example of the default option concept, suppose that tunneling by means of a 20-foot-diameter boring machine is being simulated. The user might specify that the model is to assume that a 1600-hp boring machine is to be used. Alternatively, he might not specifically assign any horsepower rating to the machine. In this case, the model would, by default, assign a horsepower rating to the machine which is reasonable, according to historical data.

The outputs of the tunneling model will be the cost information file and the output reports concerning the system and progress of the simulated excavation, as discussed earlier.

The structure of the tunneling model itself is shown in Fig. 12. The activities which are to be performed in the course of tunneling are represented by a set of subroutines. The sequencing or overlapping of

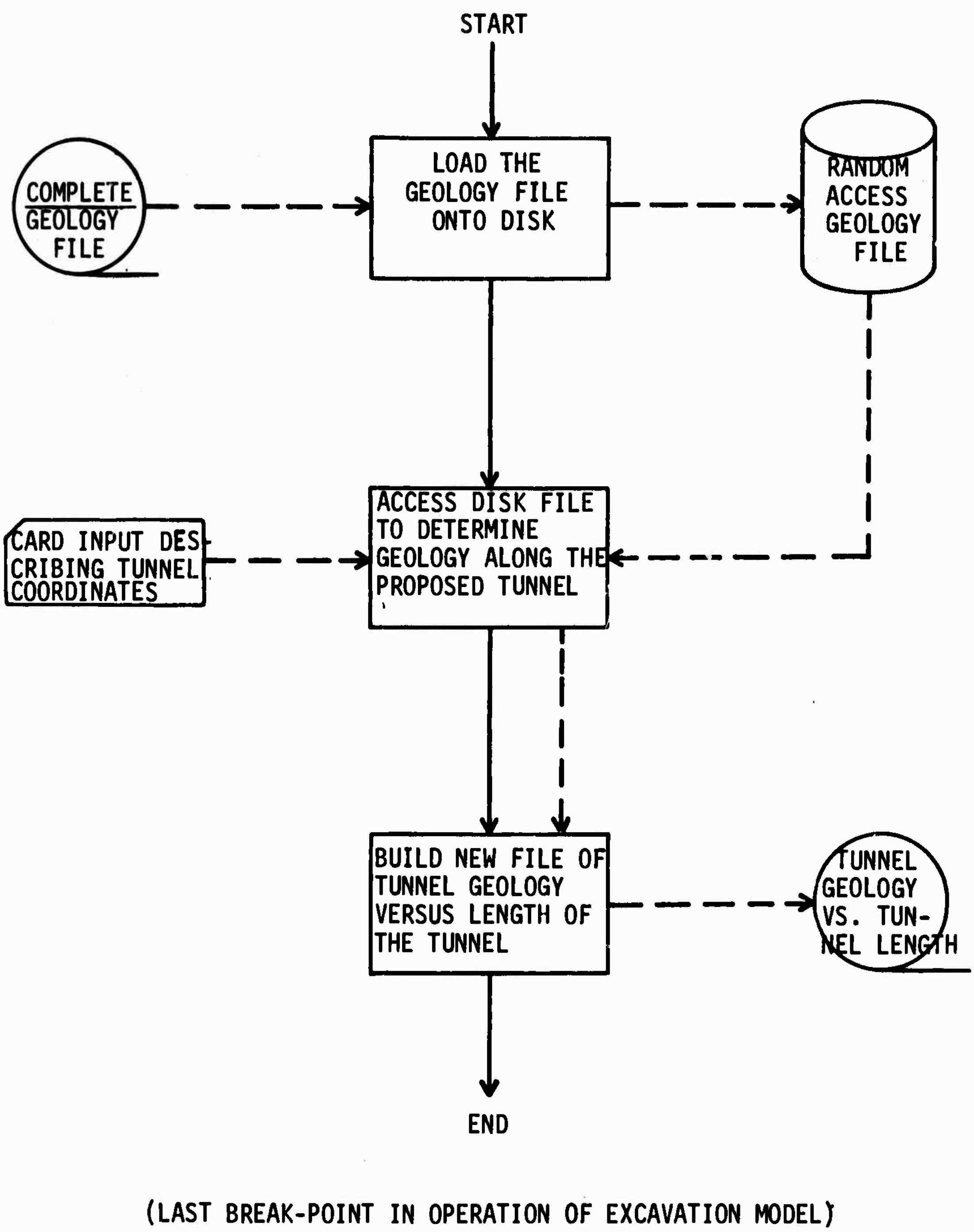


Figure 10. Tunneling Model - First Step

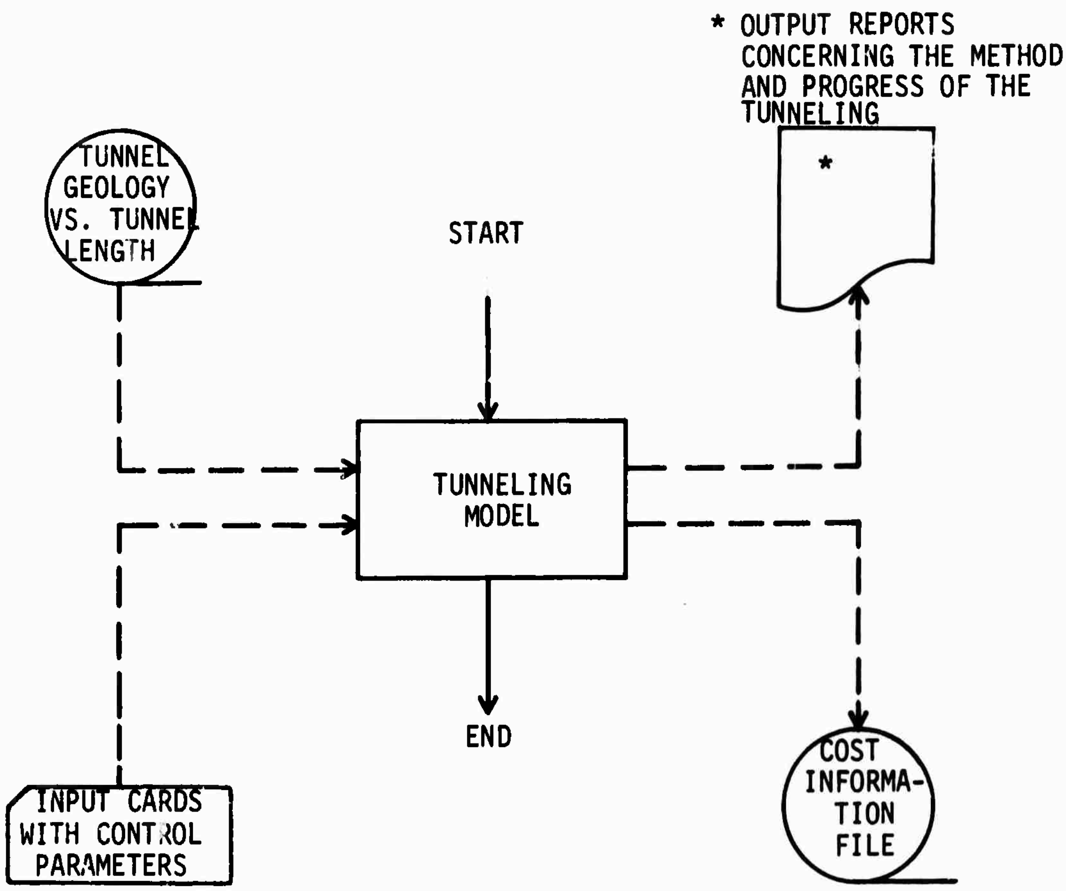


Figure 11. Tunneling Model - Main Part

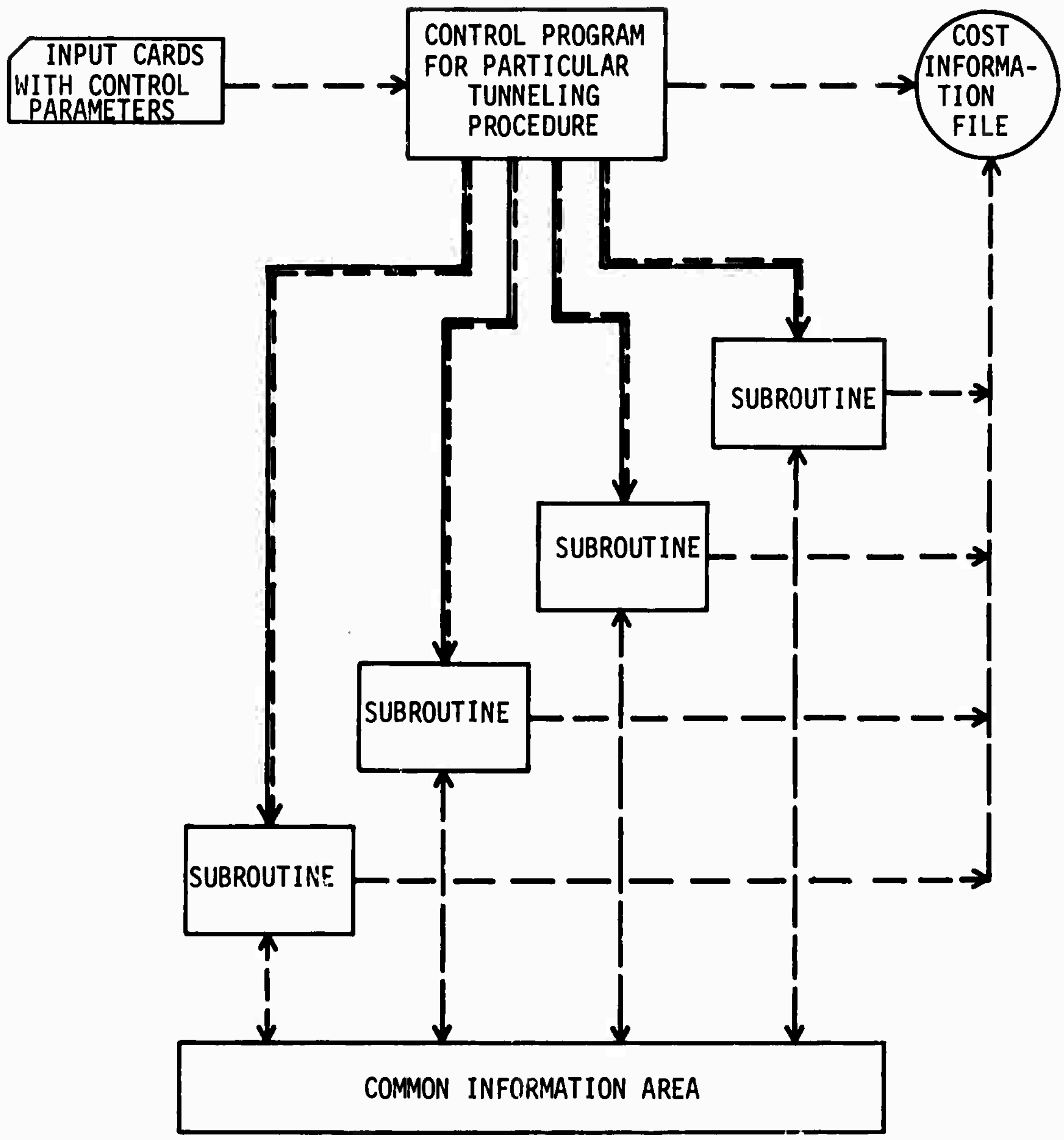


Figure 12. Tunneling Model - Structure

activities is controlled by the control program for a particular tunneling procedure. Input cards which control this sequencing and specify the performance characteristics of each activity (unless a default option is selected) are read into the control program. Information is transferred to and from a common information area to account for the interrelationships between each activity. Performance reports drawn from the common information file are printed periodically at a user-specified time interval, monthly, and at the completion of the simulated tunnel project to summarize equipment performance, availability, utilization, tunneling rate of advance, and material handling rate. Cost reports, drawn from the cost information file, are printed similarly.

An example of an assembly of activities to simulate a specific excavation system, one employing a boring machine for rock disintegration and a machine-integrated muck loader combined with rail car haulage for materials handling, is shown in Fig. 13. The solid lines represent the flow of information from the subroutines to the output. Omitted for clarity from the drawing is the logic reflecting the interaction between the subroutines. The following discussion should be sufficient to explain how this works.

The subroutine BORE represents the activity of breaking rock by boring head rotation. This subroutine accepts input and calculates output as shown in Fig. 14. Of the input, tunnel diameter must be user specified; power rate, power limit, labor rates, and time increment may be user supplied or set by CONTROL by default; rock strength comes from the file of tunnel geology versus tunnel length; and machine rotational power and specific energy may be user specified or set by BORE by default if tunnel diameter and rock strength are within certain bounds (see Sec. IV-C for the particular functional relationships derived for boring machine performance). Each performance output (volume, volume rate, advance, and advance rate) is transmitted to the common information area from which it can be drawn, as needed, by the

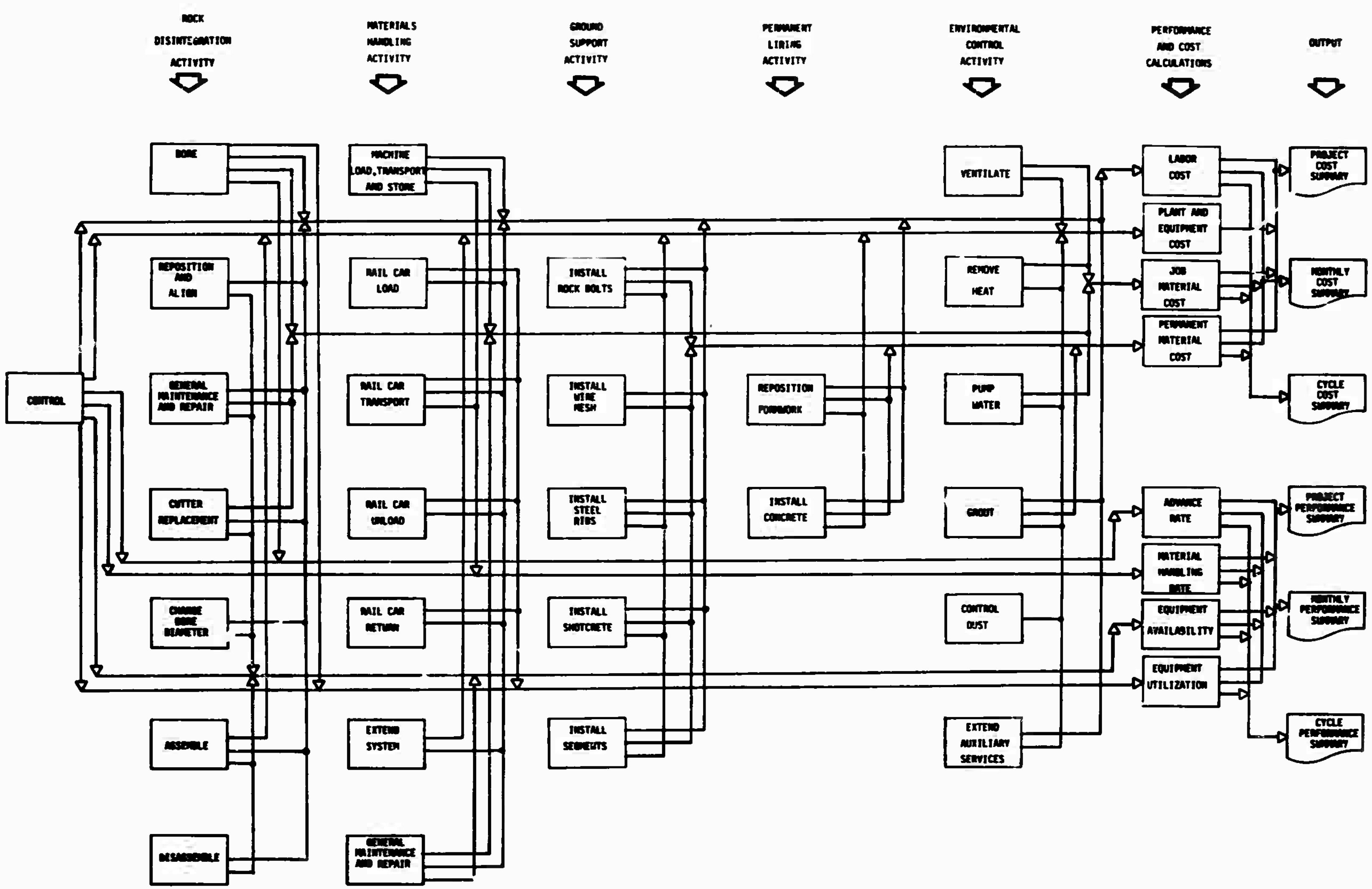


Figure 13. Subroutine Assembly to Simulate an Excavation System Employing Boring Machine and Rail Car Haulage

INPUT AND PARAMETERS	ACTIVITY	OUTPUT
Power Rate ($/kW-hr)	BORE	Volume (ft^3)
Power Limit (hp)	$O_i = f_i(I_j, P_k)$	Volume Rate (ft^3/min)
Labor Force (number)		Advance (ft)
Labor Rates ($/hr)		Advance Rate (ft/hr)
Tunnel Diameter (ft)		Job Material Cost ($)
Rock Strength (psi)		Labor Cost ($)
Time Increment (min)		
Rotational Power* (hp)		
Energy Per Rock Volume Broken* (in-lb/in^3)		

I_j : Input parameters computed elsewhere and inputted to subroutine (e.g., rock strength)

P_k : Parameters characteristic to the activity that are internally programmed (design parameters), or externally set by user (labor rates, etc.)

O_i : Output parameters computed by subroutine

$f_i(I_j, P_k)$: Functional relationships relating the output (dependent) parameters to the input (independent) or characteristic parameters.

*Optional for tunnel diameters of 6-20 ft with rock strengths of 5-30 × 10^3 psi.

Figure 14. Input and Output of the Activity BORE

materials handling activities, ground support activities, permanent lining activities, environmental control activities, and performance calculating subroutines. Likewise, similar information is drawn by BORE from the common information file concerning availability of haulage equipment, availability of labor, location of last ground support, general environmental conditions, and the need for cutter replacement or maintenance and repair of the boring machine, and this information governs the operation of BORE. In this way all of the activities are interrelated and controlled by existing conditions.

At the same time, the job material costs and labor costs are stored in the cost information file from which periodic cost information reports are printed by a set of cost calculating and reporting subroutines.

4. Cost Model

To analyze and present the results of the cost of tunneling, it has been decided to break the costs associated with the general processes down into a set of standard cost categories. The analysis is intended to provide functional relationships and unit costs to be included in the total system simulation.

It is intended, wherever possible, to break down the general process costs into the following categories:

- Direct Labor
- Job Materials
- Permanent Materials
- Plant and Equipment
- Overhead

A description of what is meant by the preceding categories follows.

a. Direct Labor

This is the cost of labor directly applicable to a specified activity, e.g., in the rock disintegration-boring machine option it will be the cost per hour of the crew required to operate the machine and any auxiliary activities included under this option. This figure is arrived at by study of past contractor usages in manning, and the prevailing union wage rates

b. Job Materials

This is the cost of the consumable items used during a given activity. Examples of this would be the cost of power used, cutter costs, and explosive costs. The input to the program will be the unit costs, i.e., cost per kilowatt-hour for power. The individual activity subroutines will calculate from its internal functional relationship the cost of power consumed for a given advance in the specified tunnel. Then for the given element, the cost of identified job materials will be summed and shown on the output records in a form discussed below.

c. Permanent Materials

This item represents the cost of materials used which form part of the permanent structure of the tunnel, i.e., the cost of rock bolts and other ground support equipment.

d. Plant and Equipment

This item represents the cost of both capital equipment, i.e., depreciable equipment such a boring machines, conveyors, trucks, and fixed plant which is required (rail, power cables, etc.).

e. Overhead

Overhead expense is a fixed percentage charge to all the elements of the excavation process to account for administration, supervisory personnel and unassigned labor.

Information concerning the progress and cost of the excavation method is a primary reason for constructing the excavation model. The progress information is printed out while the excavation simulation is in progress. The various costs incurred by the excavation method being simulated are placed in a cost information file by the subroutines of the excavation model. After the excavation simulation is completed, this file is processed by a cost-reporting system which produces standardized cost reports. This approach isolates the report-generating logic from the excavation simulation logic, thus simplifying the logic of programming involved. Figure 15 shows schematically the flow of information from the main part of the program into the cost-calculating system, and the flow between that area and the information file and reporting area.

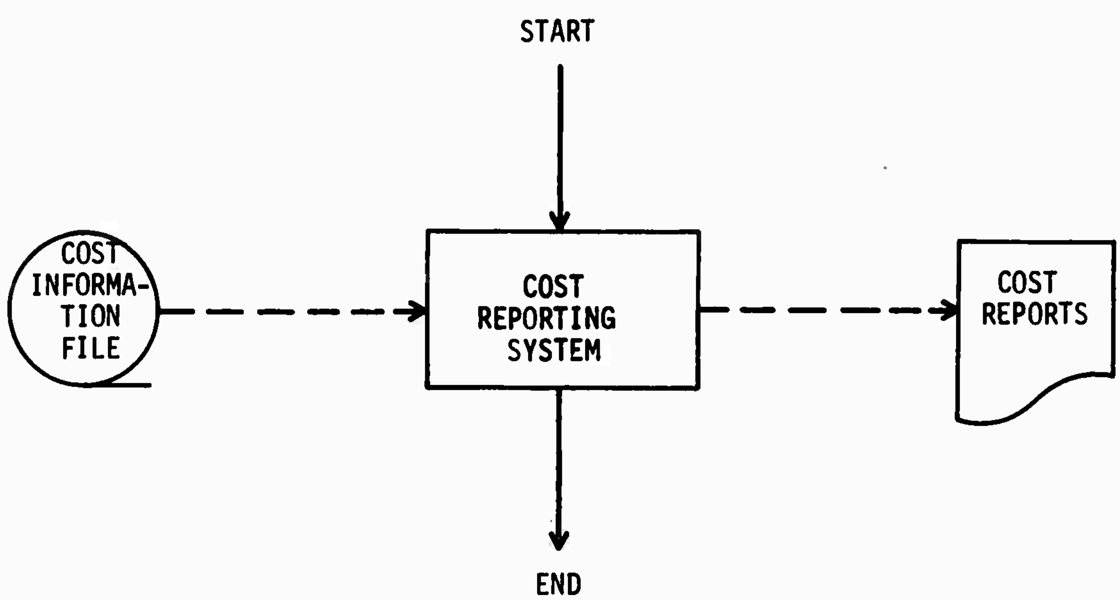


Figure 15. Cost Reporting System

Table 9 shows the form that the input data to the cost subprogram will take (the tunnel characteristics and geology being incorporated elsewhere in the program input), for a typical 10-foot-diameter tunnel. The inputs shown apply specifically for the boring machine option under rock disintegration. Other general processes within that element or other elements would have similar formats. If not supplied by the user, these inputs will be set internally by default to mutually consistent representative values.

An output example from the cost program is detailed in Table 10. It shows the breakdown of final costs by element, and category, as well as total costs. This output can also be produced at intermediate intervals in the program, determined by specific time intervals (i.e., monthly) or by a specified number of cycles in the case of cyclical operations.

C. ANALYSIS

The following subsections discuss which excavation processes have been selected for modeling, how they were selected, the activities which constitute each process, and the functional relationships which will be used to represent mathematically the performance and costs associated with each activity.

1. Selection of Processes to be Modeled

The analysis of tunnel excavation, which has been in progress throughout both the data gathering and the simulation development phases of this study, has provided a comprehensive list of the identifiable general processes associated with each element of excavation--rock disintegration, materials handling, ground support, and environmental control. This analysis has also identified and assembled the available technical and cost information on these processes. Although both data gathering and simulation development are still in progress, a preliminary list of those processes to be modeled has been formulated and appears below as Table 11.

TABLE 9
EXAMPLE OF COST INPUTS REQUIRED FOR SIMULATION

- Tunnel Characteristics (diameter, size, etc.) (assume 10-foot diameter)
- Geological Conditions Incorporated Elsewhere

	Unit Cost	Quantity	Lifetime
Element - Rock Disintegration			
Process - Boring Machine			
Category 1 - Direct Labor	$/hr 8.32	2	---
	8.01	2	---
	8.92	1	---
Category 2 - Job Material			
Power	$/kW-hr 0.02	FR	---
Cutters	$ 80	21	FR
Cutter Hubs	$220	21	FR
Category 3 - Permanent Material	---	---	
Category 4 - Plant and Equipment			
Boring Machine	$300,000	1	10,000 hr
Power Transmission System	$/ft 3.40	FR	---

Activity Related Constants		
Machine Assembly	(hr)	160.
Reposition and Align	(hr)	0.033
Bore	(ft)	5.
Change Bore Diameter	(hr)	24.
Change Cutter	(hr)	0.50
Maintenance and Repair	(%)	13.

Symbols: FR--Data Obtained from Functional Relationships

--- Input Not Applicable

Similar input forms required for other cost elements.

TABLE 10
EXAMPLE OF FINAL COST OUTPUT

Tunnel Diameter	ft
Length of Tunnel Driven	ft
Time Taken	hr
Average Advance	ft/hr
Maximum Advance	ft/hr
Vol. Material Advance	ft^3
Average Cost	$\$/ft^3$

	Direct Labor	Job Materials	Permanent Materials	Plant & Equipment	Overhead	Element Total Cost
Rock Disintegration Option-- Boring Machine	--	--	--	--	--	--
Materials Handling Option-- Conveyors & Rail Cars	--	--	--	--	--	--
Ground Support & Lining Option-- Rock Bolts	--	--	--	--	--	--
Safety & Environment Option-- Forced Air	--	--	--	--	--	--
Category Total	$					

TABLE 11

EXCAVATION PROCESSES TO BE MODELED

Rock Fragmentation
- Drill and blast
- Boring machines
- Water jet (pulsed and continuous)
- Pellet impact

Materials Handling
- A. Face to main line transport
  - Shuttle cars
  - Loaders
  - Scoop-trams (load-haul-dump equipment)
  - Shovels
  - Trucks
  - Hydraulic
- B. Main line transport
  1. Continuous
     - Conveyors
     - Hydraulic
     - Pneumatic
  2. Intermittent
     - Rail systems
     - Truck systems

Ground Support and Tunnel Lining
- No support
- Rock bolts (and wire mesh if required)
- Steel rib sets (with blocking and lagging if required)
- Shotcrete
- Concrete (poured in place and precast segments)

Environmental Control Including Health and Safety
- Forced air ventilation
- Temperature control
- Ground water control (grouting and pumping)
- Dust control
- Extension of auxiliary systems (e.g., lighting)

Geologic & Hydrologic Delineation
- Geologic and hydrologic parameters influencing excavation system performance

The processes shown in Table 11 were selected on the basis of an analysis which assigned priorities to all identifiable excavation processes. This procedure limited the scope of the effort consistent with the project time frame to those processes which were most applicable to hard rock tunneling and were sufficiently well understood to allow modeling. Others may be included at a later date.

The criteria used in the selection of the processes for modeling include the following:

(1) An examination of the inherent physical limitations and cost effectiveness of the general process related to hard rock excavation. The emphasis of this study has been more towards military applications which implies excavation in rock having a compressive strength of at least 15,000 psi. Processes that cannot handle hard rock are generally excluded.

(2) An examination of the potential for advancing the state of the art within the next 5 to 20 years. Again, because the study is guided more towards military applications, it was considered necessary to establish the potential for overcoming the limiting physical constraints or unfavorable cost-effectiveness considerations within that time frame.

(3) A review of the general state of knowledge on the general process. This review included basic or applied research and development done in the past and the availability of technical information or technical expertise to support the performance and cost analyses.

2. Performance and Cost Relationships for Each General Process

This section presents the performance equations and related information associated with those activities and excavation processes

to be modeled by computer simulation.* This material has been grouped by alternative methods available for each excavation element for expositional convenience.

It also deals with the formulation of the functional relationships related to cost. Where it is possible to model a general process, at the activity level, from a cost standpoint, that will be attempted. For a developing or novel process, however, the data may not be available to model the costs at an activity level. In this case, the calculation of the costs will be necessarily at a more aggregated general process level. Also, in certain of the conventional processes, some of the cost categories, i.e., direct labor and plant and equipment, may be accounted for on a process level, while other categories are on an activity level.

For example, under direct labor all the men may not be involved directly in a given activity, but they are still present and must be paid, awaiting the next activity in which they are involved. But under job materials one can generally distinguish materials used for a given activity directly. This is shown in the schematic of Fig. 16, where direct labor and plant and equipment are shown as calculated on a process level, and job materials and permanent materials are calculated and identified separately for each activity and then summed.

a. Element: Rock Disintegration

General Process: Boring Machine

Activities: Bore
Reposition and Align
General Maintenance and Repair
Cutter Replacement
Change Bore Diameter
Assemble
Disassemble

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*A summary list of these activities and their interrelationships may be found in Appendix I.

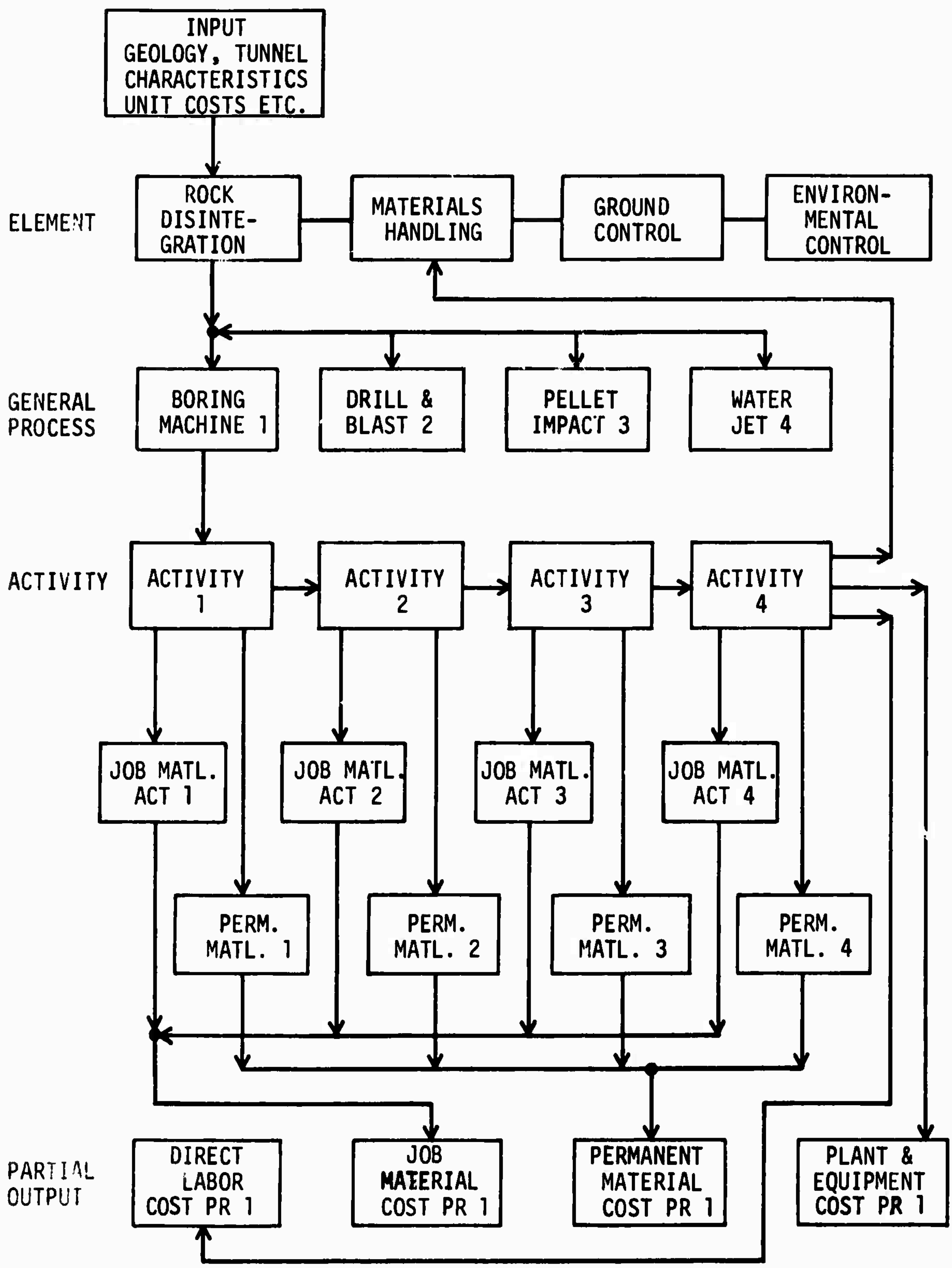

Figure 16. Flow Chart Showing Cost Calculations by Process Activity for a Specified Element

A history of boring machine characteristics and performance has been compiled and is included as Appendix II of this report. An increasing percentage of rock tunnels are being bored every year, in part due to improved designs providing lower tunneling costs and higher rates of advance.

In the past, the factors which have had the most pronounced adverse effect on the overall average advance rate were:

- Unexpected large variation in tunneling conditions (e.g., major fault zones, squeezing plastic clay, large water inflow)
- Short life of bits, cutters and bearings in very hard rock
- Lack of compatibility between the boring machine and conventional ground control and materials handling systems (a need for an integrated system)
- Variations in rock strength and hardness which affect both penetration rate and cutter change frequency
- Major equipment breakdowns resulting from manufacturing problems or operating techniques

Significant advancement of the art has come about, mostly as a result of attempts to design each machine to match the set of geologic conditions expected in each application. As a result, economical use of boring machines in both very hard rock (30,000-45,000 psi) and difficult geology is foreseen for the near future.

A representative example of a boring machine project in hard rock is the 19,970-foot-long, 12-foot-diameter River Mountains tunnel on the Southern Nevada Water Project (1968-1970). Rhyolite, rhyodacite, and volcanic lava flows were the principal rock types encountered. The maximum unconfined compressive strength was approximately 16,000 psi.

A Jarva Mark 11-12 tunnel boring machine advanced by a 2-foot stroke at a rate which varied from 0.5 to 6 inches per minute. Repositioning time was 1 minute. On a 7 1/2 hour, 3-shift per day, 5-day work week basis, the average advance attained was 36 feet per shift. Maintenance on the machine was 25% of the available excavation time, much of which was used changing cutters. Each cutter required 30 minutes to replace. The drive-motor pinion and ring gears, the hydraulic system, and the conveyor drive motor required most of the repair work.

Rock bolts were used for ground support, averaging 12 bolts per 100 feet of tunnel. It took 20 minutes to drill and install one rock bolt, on the average.

Undoubtedly the most significant tunnel boring machine project in progress at this time is the pilot bore for the 30-mile undersea high-speed railway tunnel between Honshu and Hokkaido under the Tsugaru Strait in northern Japan. Three versions of a Swiss-made boring machine, designed by Habegger, Ltd., and now produced by Atlas Copco, Inc., are being used; the first two models are 11.9 feet in diameter for the pilot bore and the third is 13.2 feet in diameter for boring a parallel service tunnel.

Rock quality and strength variations are extreme, ranging from dry volcanic ash of about 4400 psi compressive strength on the Hokkaido side to andesite with numerous water-laden faults and average strength of 40,000 psi on the Honshu side.

Under ideal geological conditions, the second 11.9-foot machine can bore 13 feet per hour, but the adverse conditions under the strait have cut the advance rate to 5 feet per hour with the best one-month advance under 300 feet.

A major requirement for a safe and successful tunneling operation in the Tsugaru Strait is a detailed knowledge of geological conditions ahead of the tunnel face. L-shaped tunnels have been excavated along the pilot tunnel to provide drilling stations from which horizontal drills can probe 2000 feet ahead of the boring machine. There are plans now for using larger drill pipes and a special in-hole drive that may allow probes of up to 3 miles.

(1) Performance

Present state-of-the-art performance of boring machines, for the purpose of the simulation, is derived from curves fit to historic data. An empirical approach was selected because the mechanism of rock fracture by rolling cutter, carbide inserts, and drag bits is not sufficiently understood at this time to allow physical modeling.

The rate of advance R of a boring machine can be expressed as

$$R = \frac{P}{AE}$$

where P = power output of the machine

A = tunnel cross-section area

E = energy per unit volume of rock broken*

Some representative data[24] for the energy per unit volume of rock broken of boring machines is plotted in Fig. 17. Also shown in this

*This energy parameter, actually a measure of machine-rock interaction, is frequently referred to as the "specific energy" of rock fragmentation. It is often misconstrued as an inherent property of the rock or of the rock fragment size distribution. The authors have decided to avoid the use of the term specific energy because of the possibility of misinterpretation, and because the more widely accepted usage of the modifier "specific" in thermodynamics identifies an intensive parameter which has been derived from an extensive one by dividing by the mass. Thus, in the International System of Units (SI), specific energy has the units J/kg.

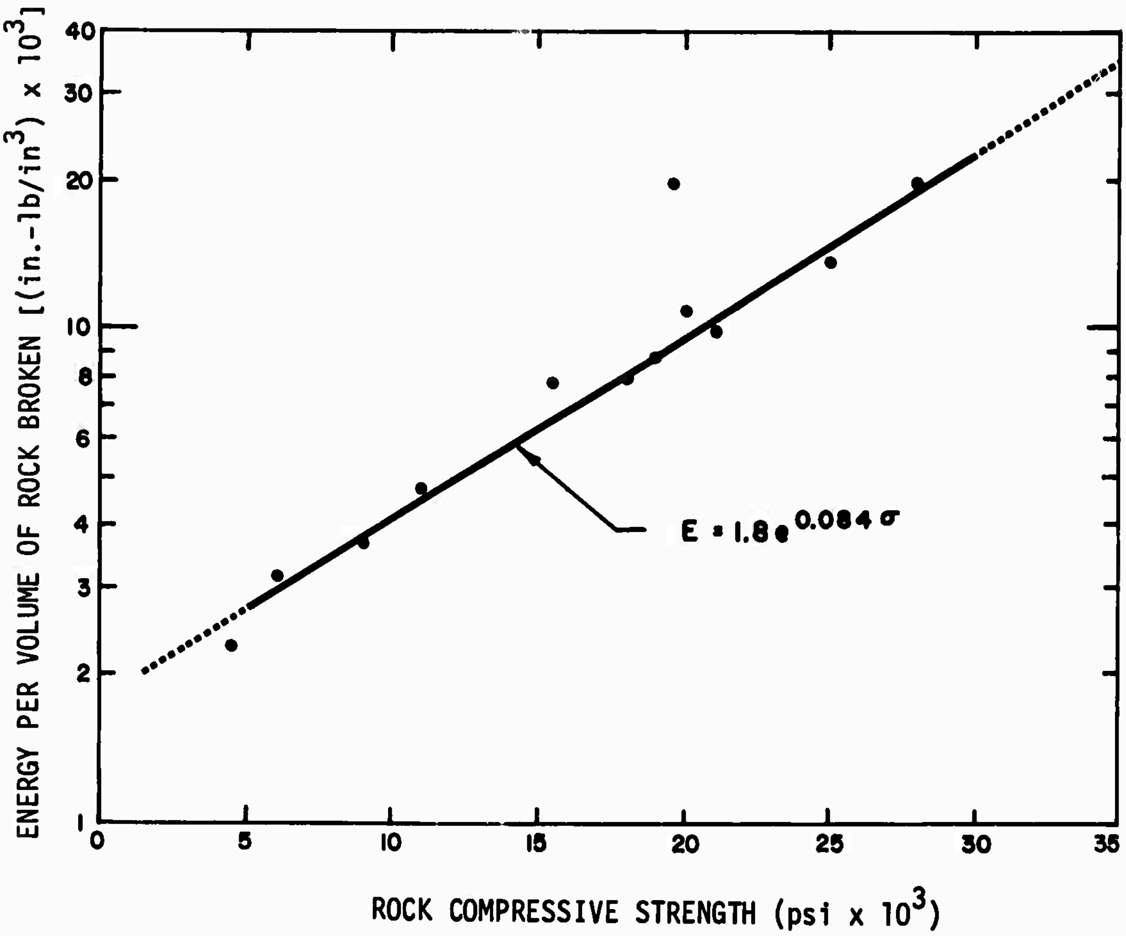

Figure 17. Boring Machine Performance[24]

figure is the relationship incorporated in the computer subroutine BORE to represent state-of-the-art performance of boring machines, which is derived from a least squares fit of the data; it gives an adequate representation of performance for rock strengths between 5000 and 30,000 psi:

$$E = 1.8e^{0.084\sigma}$$

where E = energy per volume rock broken, $(\text{in-lb/in}^3) \times 10^3$

σ = rock compressive strength, 10^3 psi

Figure 18 gives approximate ranges of compressive strengths for some common rock types.

No accurate information of the actual power output of a boring machine under varying circumstances has been found. As a consequence rated rotational horsepower of the individual machines has been interpreted as power output. The energy per volume has been calculated according to the volume of rock broken off for this amount of rated horsepower available. The machines generally operate at some undetermined fraction of rated horsepower. Yet for our purposes, this simplification which yields a consistent set of data which allows prediction of rates of advance from machine rated horsepower is desirable. It might be noted that the added horsepower used to drive the hydraulic system, which is separate from the rotational power, is not included in rated horsepower. It is generally less than 10 per cent of the rotational power.

There is a fairly consistent trend to greater machine horsepower with greater tunnel diameter (Fig. 19). This trend represents no more than historical information and it may not necessarily represent the correct machine horsepower for a given situation, it nevertheless reasonably represents state-of-the-art machine characteristics and as such has been included in the simulation as a relationship to provide the power value

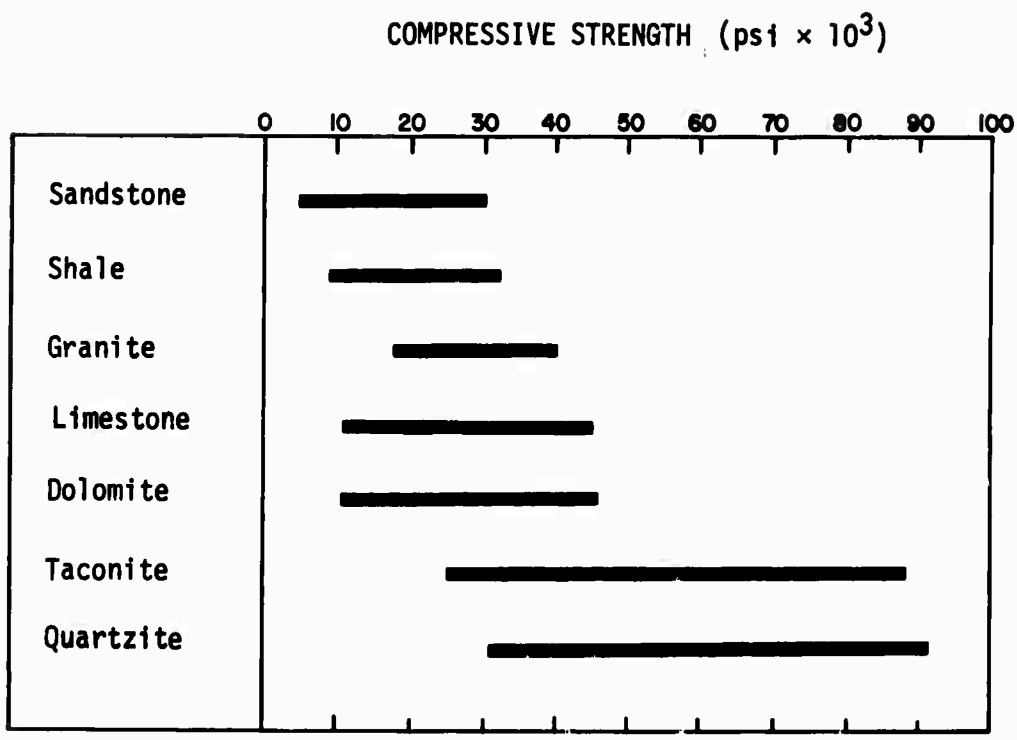

Figure 18. Range of Compressive Strength for Some Common Rock Types

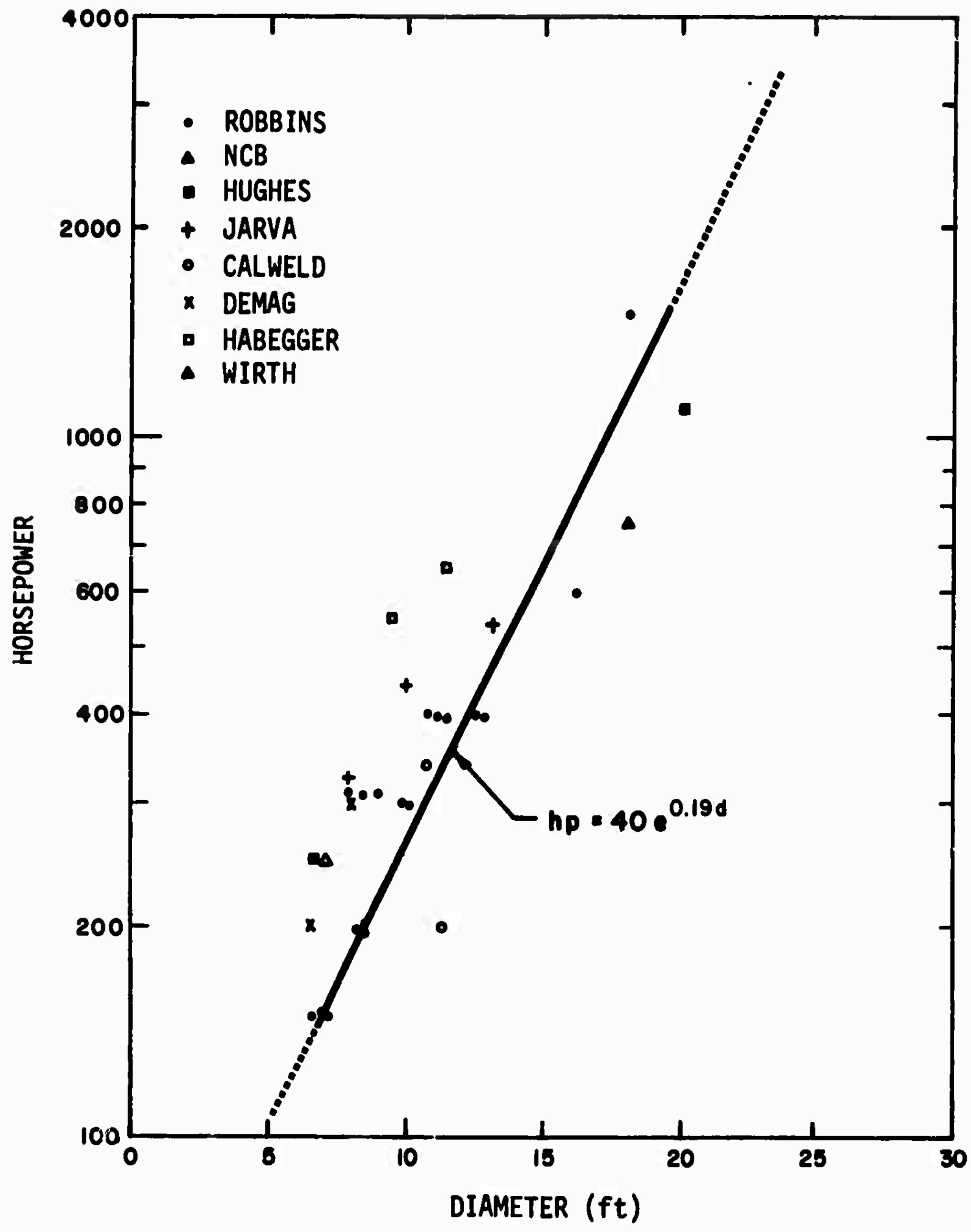

Figure 19. Horsepower Versus Tunnel Diameter Trend for Tunnel Boring Machines

which is used if the user does not specify one. This relationship may be used to represent machine horsepower for tunnel diameters between 6 and 20 feet. The relationship is

$$hp = 40e^{0.19d}$$

where hp = rated rotational horsepower

d = tunnel diameter, ft

Some information on characteristic periods of time for maintenance, cutter changes, repositioning, and activities other than boring has been included in Appendix II and will serve as a preliminary guide to scheduling these activities in the model. The user of the simulation will have the option of specifying these periods of activity as he desires.

During the initial phase of tunneling simulation development, the activities associated with boring machine operation other than BORE will be treated as appropriate fixed increases in time and cost each time they are performed. These values, and the frequency with which they are incurred, will be selected empirically. Subsequent revision of any of these subroutines to incorporate analytical material which is available is easy because the simulation is modular.

(2) Direct Labor Cost

A review of the usage of boring machines in a series of projects for the Bureau of Reclamation[25] along with discussions with manufacturers reveal that typical manpower requirem,ents per shift, associated with a boring machine, are as given in Table 12. It should be emphasized that the numbers given as labor requirements can and will vary according to the efficiency of the contractor. However, Table 12 represents realistic average manpower figures; and should the user wish to change them to determine their effect on total system costs he can do so through the input file.

TABLE 12

BORING MACHINE (DIRECT LABOR)
MANPOWER PER SHIFT

Tunnel Diameter	8'-14'	14'-20'	20'-30'	Washington, D.C., Area Hourly Costs*
Machine Operator	1	1	1	$8.32
Miners	2	3	4	$8.01
Electrician	1	1	1	$8.92
Mechanic	1	1	1	$8.32

*Includes 25% fringe benefits, FICA, etc.

The wages shown are those pertaining presently to the Washington, D.C., metropolitan area and include 25% for fringe benefits and other costs to the employer (social security, etc.). The cost of overtime at 1 1/2 times the base pay over 40 hours will be extra. The source of the data is the Wage and Hour Division of the U.S. Department of Labor. Labor costs will vary greatly over the country because of varying productivity and availability of skilled manpower. There is a difference by as much as a factor of 3 between costs in the most and least productive parts of the country. Highly urbanized areas have some of the worst productivity records because of labor availability plus other constraining factors such as environmental restrictions. Wage rates will be a user input consistent with experience in the area in which he is interested.

Table 13 gives examples of typical activity constants which will be incorporated into the program. These can be overridden by the user if desired. The criteria involved in determining when an event such as cutter change occurs are described under the appropriate job material section. The units listed in the table are those which one replication of the listed activity will take; they should not be construed as the intervals between replications.

TABLE 13

TYPICAL BORING MACHINE ACTIVITY DEFAULT CONSTANTS USED IN PROGRAM (USER MAY OVERRIDE)

Machine Assembly	160 hr
Reposition and Align	2 min
Continuous Bore Advance	3 ft
Cutter Change Time	30 min/cutter
Change Bore Diameter	24 hr
General Maintenance & Repair	13% available time

(3) Job Material Cost

The job materials (or consumable items) associated with a boring machine are basically (1) electrical power, and (2) cutters. Power cost is calculated quite simply from the rated horsepower of the machine motors, the time that the machine is in operation boring on the rock face, and the input unit of electricity cost per kilowatt-hour.

$$(\$) \text{ Power Cost} = (\$/\text{kW-hr}) \frac{\text{hp}}{1.34} \Delta t$$

where Δt = time in hours. Cutter changing is a much more important item. In fact, along with direct labor costs it is one of the prime factors determining whether a boring machine is the most economical choice for a given job.

Frequency of cutter change depends on rock strength, rock abrasiveness, tunnel diameter, and the total number of cutters on a given boring machine. It is current practice to schedule cutter replacement during the general maintenance and repair of the machine usually on a weekend shift, when possible. Harder and more abrasive rocks may cause more cutter wear and require more frequent cutter replacement. Many manufacturers calculate cutter costs by first assuming cutter layout and taking the sum of radii of all cutters to find an average radius and corresponding average cutter circumference traveled during one revolution. The cutters are assumed to be able to travel a given number of linear feet while rolling against the rock face before wearing out. Typical figures are 400,000 linear feet for a sandstone and 700,000 to 1,000,000 linear feet for shales. The figure is primarily dependent on the relative abrasiveness of the rock. In estimating the abrasiveness, one can use a variety of tests to determine the mineral content and grain size to produce a weighted Mohs' hardness for the rock (Fig. 20).

Figure 21 shows the cutter costs in dollars per cubic yard of material removed as a function of the rock hardness shown for three

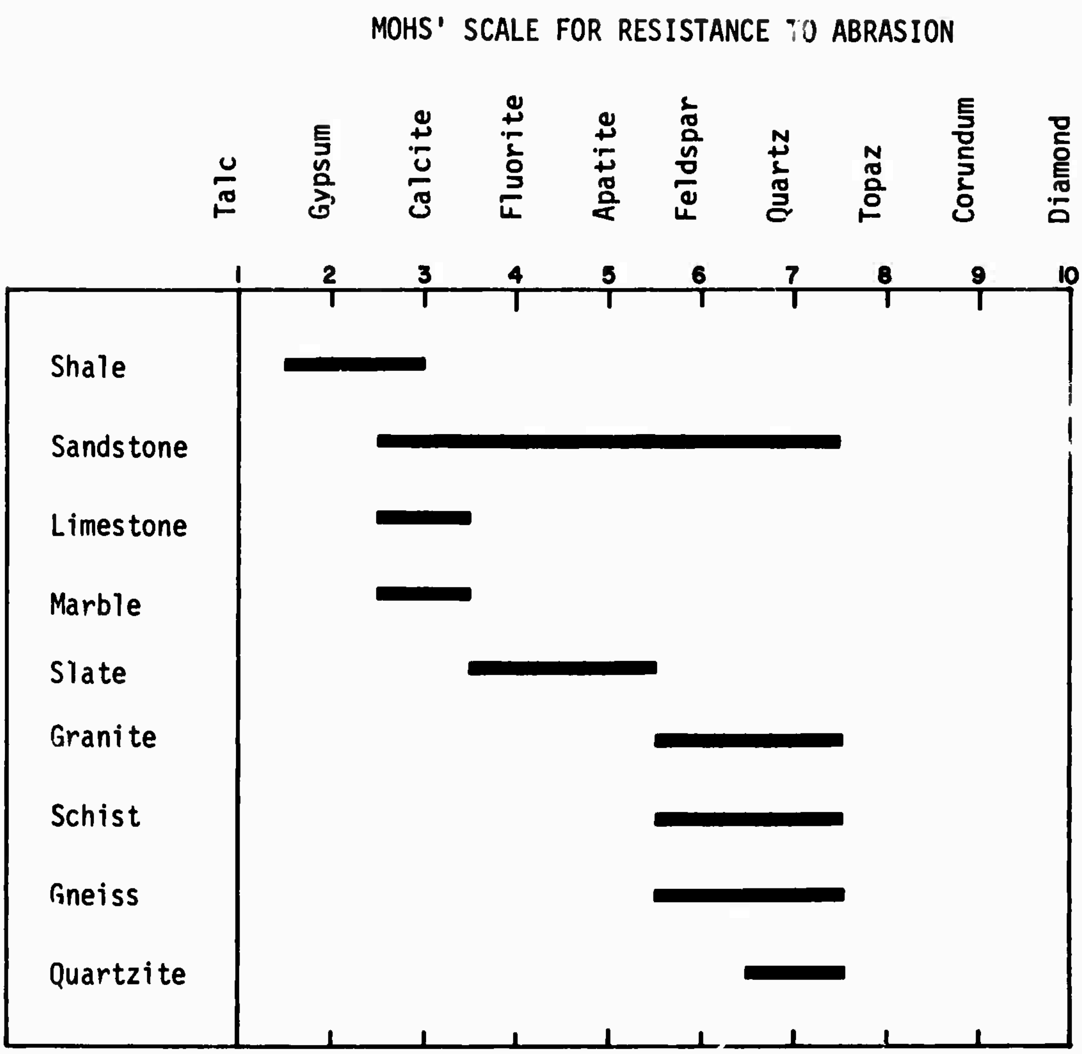

Figure 20. Approximate Mohs' Ratings for Some Common Rock Types

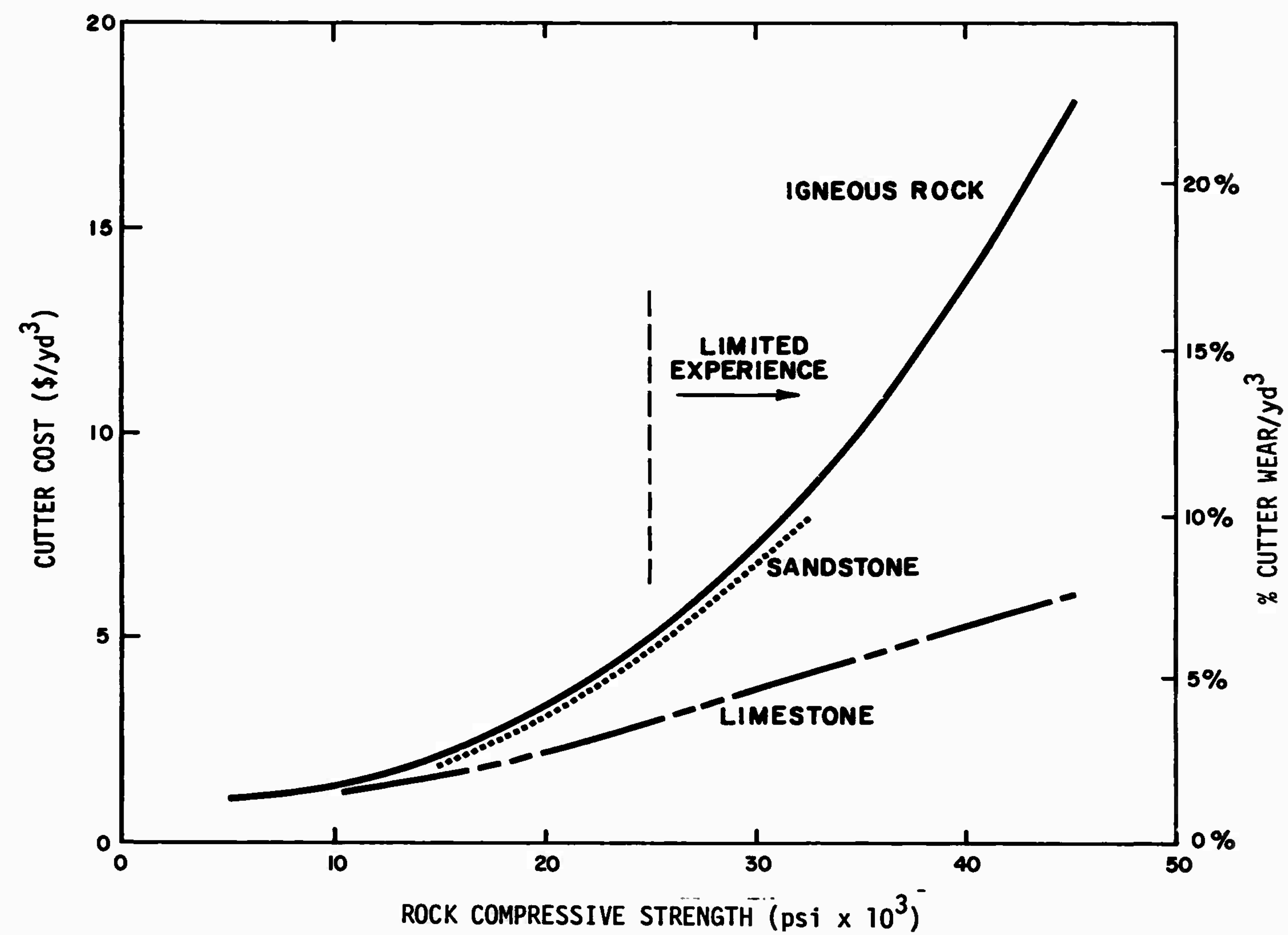

Figure 21. Hard Rock Cutter Bit Costs--Present Day Best Experience

different types of rocks covering the range of expected abrasiveness. The results shown are taken from Ref. 26 weighted to reflect current capabilities. The design of cutters is a constantly and rapidly evolving technology, and with this evolution the cutter costs are going down with experience. Caution must be applied to the use of these curves since the experience on which they are based was severely limited above 25,000 psi hardness. There may exist some limiting maximum rock hardness through which present-day cutter materials will not penetrate. Further research is necessary to identify what this limiting value might be.

It should also be noted that this averaging method fails to account for the more frequent failure of the gauge cutters (at the boring head periphery). It is generally believed that this failure is due to the particular stresses applied to these cutters and to their repeated travel through the broken rock in the invert.

Polynomial expressions that approximate the curves of Fig. 21 are (σ = compressive strength, 10^3 psi):

Limestone (least abrasive)

$$(\$/yd^3) \text{ Cutter Cost} = .216 + .844\sigma + .997\sigma^2/10^3$$

for $10 < \sigma < 45$

Sandstone (medium abrasiveness)

$$(\$/yd^3) \text{ Cutter Cost} = .7 + .257\sigma/10^2 + .442\sigma^2/10^2 + .815\sigma^3/10^4$$

for $15 < \sigma < 33$

Igneous Rock (most abrasive)

$$(\$/yd^3) \text{ Cutter Cost} = .883 + .257\sigma/10^2 + .442\sigma^2/10^2 + .815\sigma^3/10^4$$

for $10 < \sigma < 45$

To the cutter bit costs must be added the cost of bearing replacements. This is an event that on the average must be performed every six changes in cutter bit, and its cost aggregates as follows:

Total Bearing Cost = .5 Total Cutter Bit Cost

(4) Plant and Equipment Costs

The cost of a boring machine can be seen from the plot in Fig. 22 to be a function of the installed horsepower, and from Fig. 19 the horsepower is seen to be a function of diameter:

Machine Cost = $1000 hp

where hp = $40e^{+.19d}$ (d in feet). These results, which are derived from actual costs, give a guide to the capital costs involved. The user of the program may change these values if he wishes. The lifetime of machines will vary according to the conditions of use and the maintenance provided. However, a formula which will be used to approximate machine cost per linear foot of tunnel driven is

$$\frac{\text{Machine Cost (\$)}}{\text{(10,000 hr)} \times \text{(Penetration Rate) (ft/hr)}} = \text{\$/ft}$$

The figure of 10,000 hr as the lifetime of the machine can be changed by the program user. The time is calculated as that in which the machine is in actual operation; down time is not included. From this equation the machine write-off in dollars per foot can be determined for a given advance rate.

There is an additional cost for the power transmission system:

Cost Transmission System = $3.40 × Length (ft)

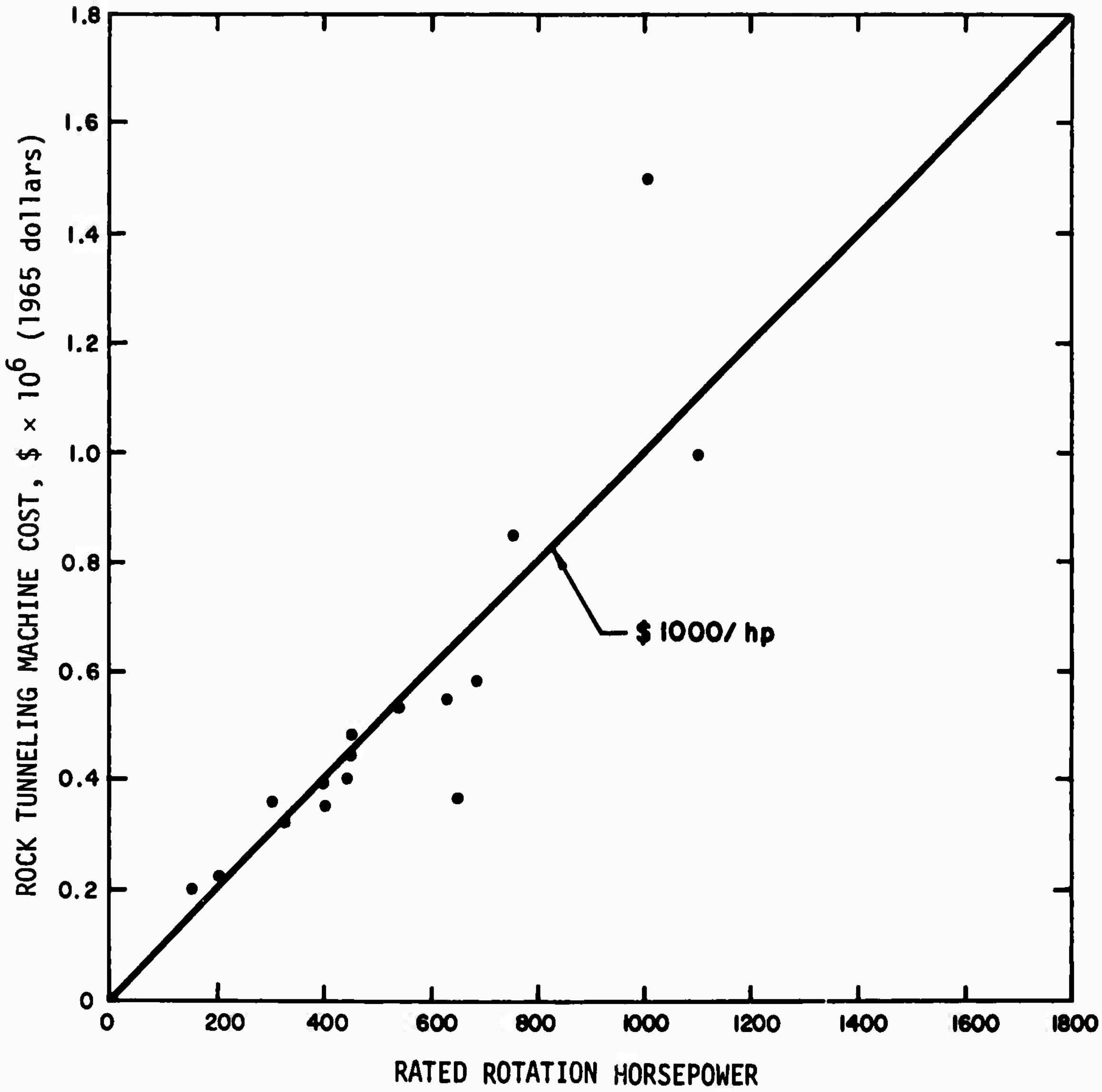

Figure 22. Rock Tunneling Machine Costs Related to Machine Rated Horsepower

(5) Permanent Material Cost

Permanent materials which can be thought of as the fixtures which remain in the tunnel after construction (supports, utility lines, etc.) are associated primarily with the other elements of excavation, especially ground control. They are not a significant cost associated with boring machine operation.

b. Element: Rock Disintegration

General Process: Conventional Drill-and-Blast

Activities: Set Alignment
Drill Holes
Set Charge
Evacuate and Shoot
General Maintenance and Repair

The drill-and-blast process of excavating is the standard and most often used process for hard rock. There are inherent cycle delays in the process during which no rock can be loaded for removal because loading must be stopped for drilling and shooting; and everything must be stopped after shooting to allow time for exhaust of explosive fumes. The high intermittent rate of breakage of rock, however, is sufficient to counterbalance these delays, thus often making drill-and-blast the most rapid, economical, and sometimes the only practical, means of excavating hard rock today.

For the above five activities, a major fraction of the time spent during drill-and-blast is spent drilling the holes into which the explosive charges are placed. Our preliminary effort therefore has been identifying drill techniques and mathematically portraying their performance.

There is a wide range of drill types and methods of mounting drills on a drill jumbo. Most drilling in hard rock tunnel construction is done

with a percussion drill having either rifle-bar rotation or some separate positive method of drill rotation. Sinkers and jackhammers, designed to be hand held, vary from a light 30-pound drill to a heavy 70-pound drill. Feed legs and jacklegs, which are sinker drills mounted on an air feed leg, are used generally for both lateral and overhead drilling. Drifters are self-rotating drills which are screw or chain fed. Burn-hole drills are drifters used to drill the large holes on a burn-cut pattern of shooting.

Drifter drills are suspended from jibs mounted on drill jumbos which serve as working platforms and house all facilities required for drilling a round: pumps, air and water connections, lights, and ventilation. The jumbo may also be used for loading the holes, placing supports, and in some cases handling muck cars.[27]

(1) Performance

Drilling rate, R, can be expressed as

$$R = \frac{P}{AE}$$

where
P = power output of the drill
A = hole cross-section area
E = energy per rock volume removed

Some representative data for energy per volume relationship of percussive drills in hard rock is shown graphically in Fig. 23. Also shown in this figure is the relationship incorporated in the computer subroutine which is derived from a least squares fit of the data for rock strengths below 50,000 psi. For rock strength above 50,000 psi the observed data are inconclusive but suggest an energy per volume range of approximately 0.05 to 0.075 in.-lb/in^3.

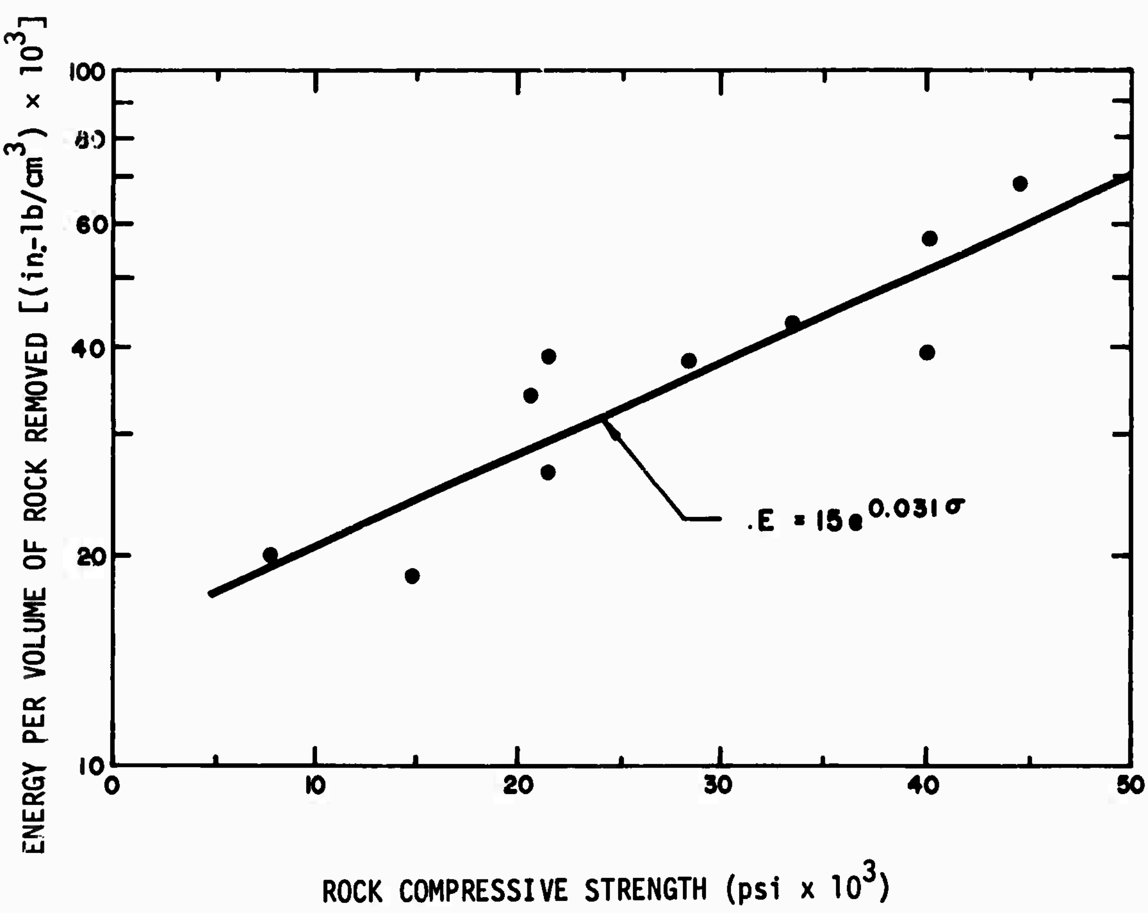

Figure 23. Percussive Drill Performance[28,29]

The relationships included in the computer model are:

$$E = 15e^{0.031\sigma}$$

where E = energy per rock volume removed, in.-lb/in^3

σ = rock compressive strength, 10^3 psi between 5000 and 50,000 psi

or

$$E = 0.06 \text{ in.-lb/in}^3$$

for $\sigma > 50{,}000$ psi.

The power output of a drill may be calculated to be the number of piston blows per minute times the energy in each blow. The following formulas have been shown by Hustrulid[30] to have general applicability to percussive drills in hard rock:

$$P = fE_p$$

$$f = 22\sqrt{\frac{6pAg}{Sw}}$$

$$V_S = 0.68\sqrt{\frac{SpAg}{6w}}$$

$$E_p = \frac{1}{2}\frac{w}{g}V_S^2$$

where A = area of piston head (in^2)

E_p = piston energy (ft-lb/blow)

f = blow frequency (blows/min)

g = acceleration of gravity (fps^2)

P = power output (ft-lb/min)

p = applied air pressure (psi)

S = piston stroke (in.)

V_S = piston striking velocity (fps)

w = weight of piston assembly (lb)

It is intended that the required input to the computer subroutine which calculates drill performance will be the power output of the drill. Drill manufacturers can provide the specific information required in the above equations.

The analysis of the blasting process itself which may derive the powder factor* as a function of tunnel geometry and geology has not been completed at this time. Each of the other activities associated with conventional drill-and-blast, as in tunnel boring machine operation, will be set as empirical values of cost and time spent during the performance of the activity. In this case the value may depend on the number of holes drilled in the tunnel face.

(2) Direct Labor Cost

Drill-and-blast is a more labor-intensive process than the boring machine. A typical set of labor crews for different diameter tunnels to be used in the simulation are shown in Table 14. As can be seen, the number of men to be used for drilling will increase with the rock face area. These data are subject to interpretation since electricians and mechanics will have duties other than maintaining the drills. For example, they may also be concerned with the maintenance of the equipment for materials handling.

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*The powder factor is the number of pounds of powder required per cubic yard of rock broken.

TABLE 14

DRILL-AND-BLAST (DIRECT LABOR)

MANPOWER PER SHIFT

Skill	Tunnel Diameter 12'	15'	25'	Washington, D.C., Area Hourly Costs
Foreman	1	1	1	$8.32
Miners	3	4	10	7.20
Mechanic	1	1	2	8.10
Electrician	1	1	1	8.92
Shifter	1	1	1	7.20

The type of activity, the time required to perform it, and the labor involved will determine the direct labor costs in the drill-and-blast process. These activities include the following:

- Drill Holes

The number of holes required is a function of (1) the tunnel diameter, and (2) the compressive strength of the rock. The volume of rock blasted away is dependent on the depth of drilled holes which is limited by tunnel diameter.

The following has been deduced from Ref. 27 as typical average experience. The number of holes (n) required in the rock face as a function of tunnel diameter (d) is

$$n = d + (1/12)d^2, \quad \sigma > 30,000 \text{ psi}$$

$$n = .875[d + (1/12)d^2], \quad \sigma > 30,000 \text{ psi}$$

The user will have the option of using his own values of n in the computer program. If the drill penetration in linear feet per hour = R, and the length of the hole to be drilled = ℓ feet,

$$\text{Time to drill face } (T_d) = \frac{\ell}{R}\frac{n}{W}$$

where W is the number of drillers employed.

- <u>Setting the Charge</u>

  The time for this activity is given by

$$T_s = \frac{4}{60}\frac{n}{W} \text{ (hr)}$$

- <u>Evacuation and Blast</u>

$$\text{Time} = \frac{15}{60} \text{ (hr)}$$

- <u>Maintenance and Repair</u>

  This accounts for time spent on changing drill bits, jumbo maintenance, etc. The representative amount of time (and therefore labor cost) involved in the activity still has to be determined. It may, of course, be user specified. The cost of supplies is significant and will be calculated in the job material section. The direct cost for a drill-and-blast cycle is then the labor rate times number of men involved times time for a complete cycle.

(3) Job Material Cost

The job materials involved with this process are (1) drill bits and steel costs, and (2) explosives and associated materials. Drill bits will typically have a life of 200 linear feet in granite. A standard bit costs \$20; therefore, the bit cost per round in granite is given by

$$\text{Bit Cost (\$ per Round)} = n\ell\frac{20}{200}$$

Longer drill-bit life occurs in less abrasive rock and would reduce bit costs proportionally. The expected life in other rock has not yet been identified for use in the simulation. The relationship for granite, may be used as a conservative formula for drill bit cost.

There is an associated steel cost and the cost of burn cut bits. This can be costed separately, or taken as a fixed percentage of the drill bits

Steel Cost + Burn Cut Bits = .5 Standard Bit Costs

The cost of explosive materials, associated with the evacuate and blast activity, includes the cost of caps, powder, and explosives, and is determined from the number of holes per round, and the pounds of powder required per cubic yard of excavation to break the material.

$$\text{Cost of Primer Powder per Round} = n \times \text{lb powder per hole} \times \$/\text{lb}$$
$$= n \times .5 \times .2 \tag{1}$$

$$\text{Cost of Caps per Round} = n \times \$/\text{Cap}$$
$$= n \times .3 \tag{2}$$

$$\text{Cost of Explosive per Round} = \text{Volume Excavated (Cubic Yards)} \times \text{lb Explosive/Cubic Yard Removed} \times \$/\text{lb}$$

$$= \frac{\pi D^2}{4} \cdot \frac{\ell}{27}\left[7.5 - \frac{D}{10}\right].06 \tag{3}$$

The relation for the efficiency of the explosive, i.e., pounds of explosives required per cubic yard material removed again represents blasting in granite; further analysis may identify, or the user may specify alternative powder factors for other geologies.

Cost of Wire and Miscellaneous Items = \$1/linear ft = ℓ (4)

The total cost of the job materials (powder + explosives) per round = the sum of items (1), (2), (3), (4) above.

(4) Plant and Equipment Cost

The amount of plant and equipment used will vary with the tunnel diameter (Table 15). The variable quantities are the number of drifter drills, jibs, and positioners. The number increases with tunnel diameter in such a way that the time for drilling in cycle time will remain approximately the same with varying diameter for a given compressive strength of rock.

(5) Permanent Material cost

None Required

TABLE 15

DRILL-AND-BLAST PLANT AND EQUIPMENT

Plant and Equipment Used	Number Required for Tunnel Diameter			Cost/Unit $
	12'	15'	25'	
Jumbo	1	1	1	30,000
Burn Cut Drill	1	1	1	11,500
Drifter Drill	3	4	10	5,800
Jib	3	4	10	5,200
Drill Positioner	3	4	10	2,800

c. Element: Rock Disintegration

General Process: Water-Jet (continuous and intermittent)

Activities: Reposition and Align

Jet Impact

General Maintenance and Repair

High-velocity water jets, both steady and pulsed, are of interest for rapid excavation in hard rock because such jets can fracture the hardest rock by high-impact pressure and fluid shear forces. Rock disintegration by jet impact, utilizing the dynamic and static mechanical stresses in the rock, appears adaptable to a wide variety of geologic conditions, rock types, and environments, and may be particularly suitable for arbitrary geometries of excavation as well. As potential rock disintegration devices in a rapid excavation system, water jets offer the attractive advantages of minimal cutting tool wear and flexible response to a wide variety of conditions.

(1) Performance

The performance of water jets is determined in part by the physical processes involved in jet formation and impact which have been described in an earlier memorandum.[31] The effectiveness of water jets in breaking hard rock has been examined experimentally by others, and their results are summarized as follows.

Figures 24, 25, and 26 summarize for three types of rock the results of Oak Ridge National Laboratory studies of rock fragmentation by a continuous jet of water.[32]

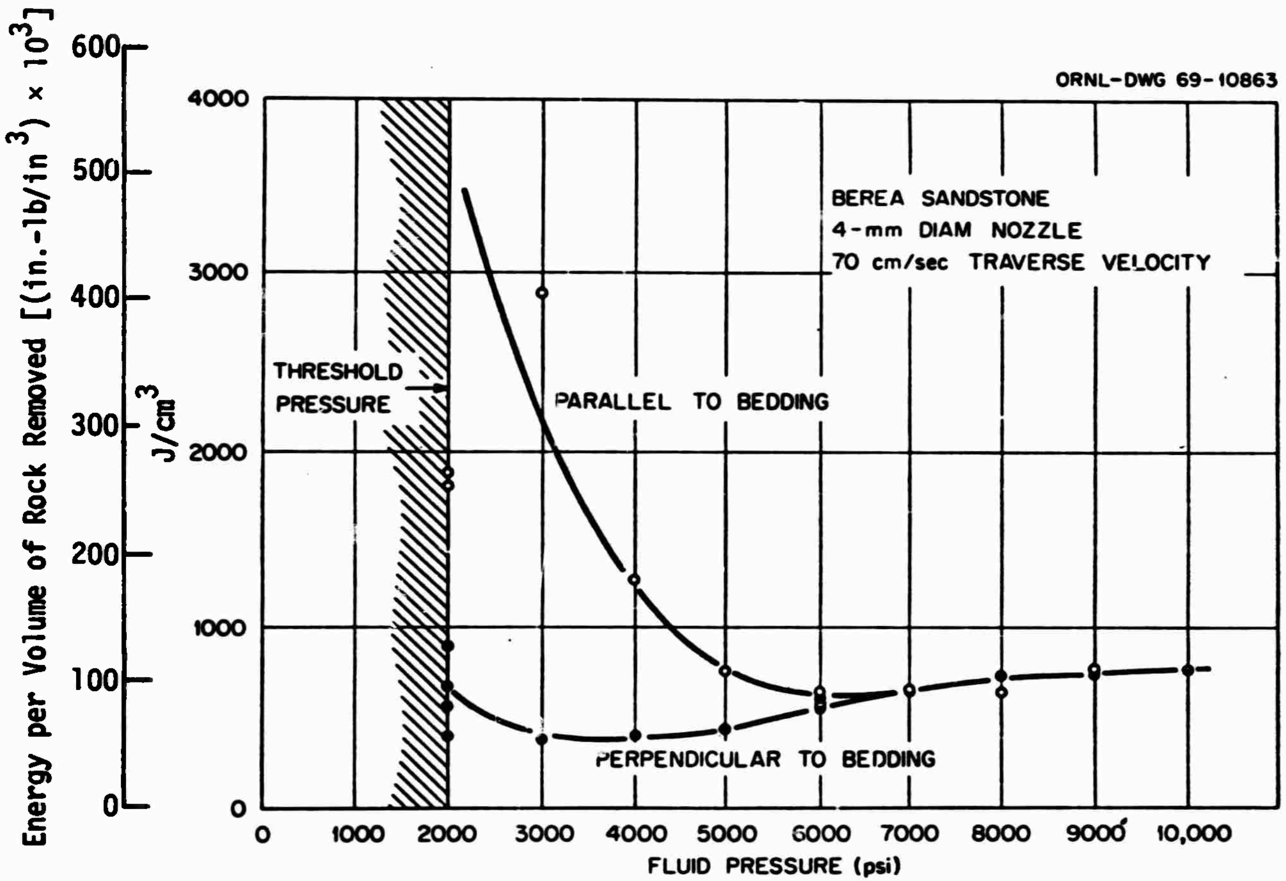

Figure 24. Energy per Volume of Rock Removed as a Function of Fluid Pressure for Berea Sandstone[32]

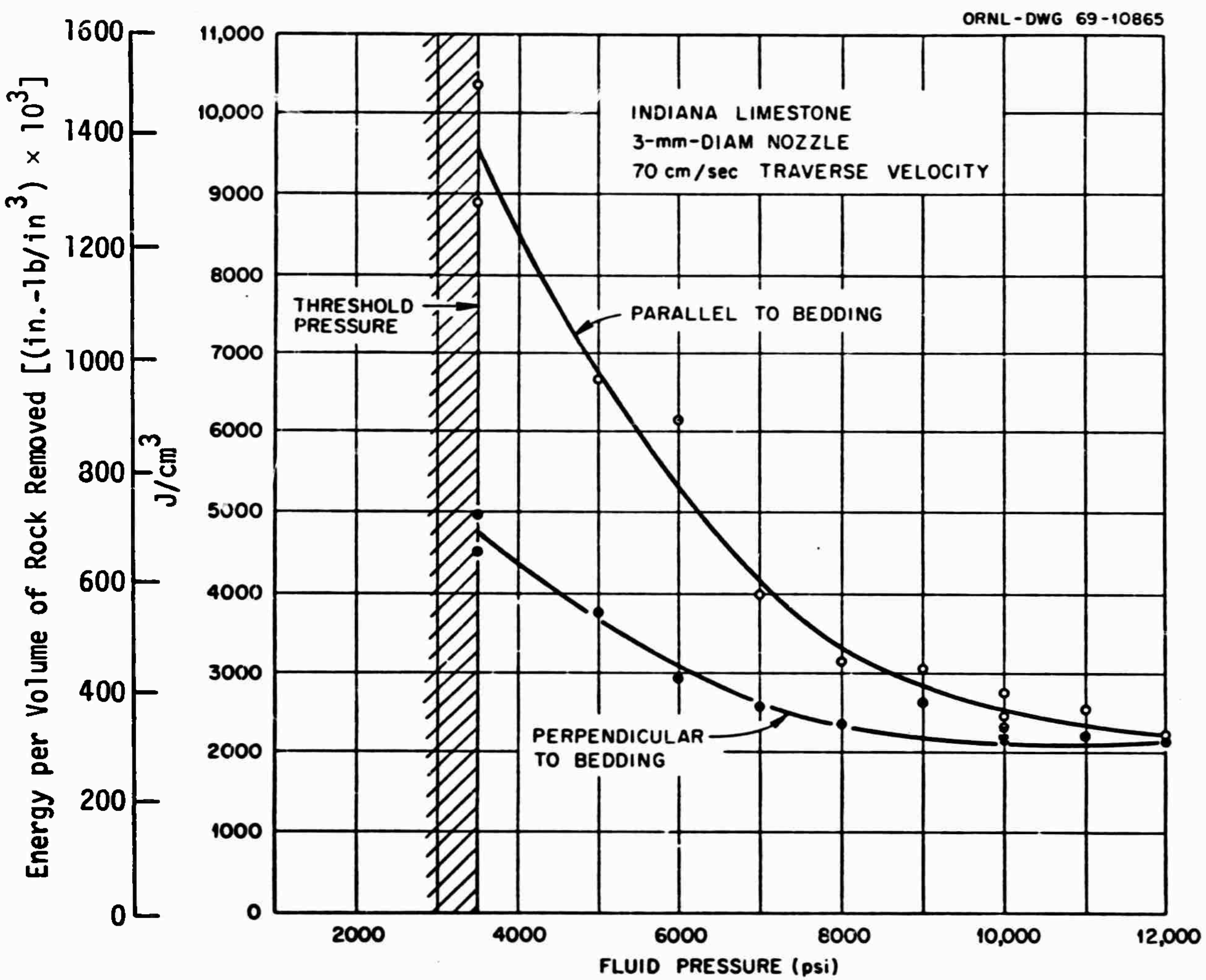

Figure 25. Energy per Volume of Rock Removed as a Function of Fluid Pressure for Indiana Limestone[32]

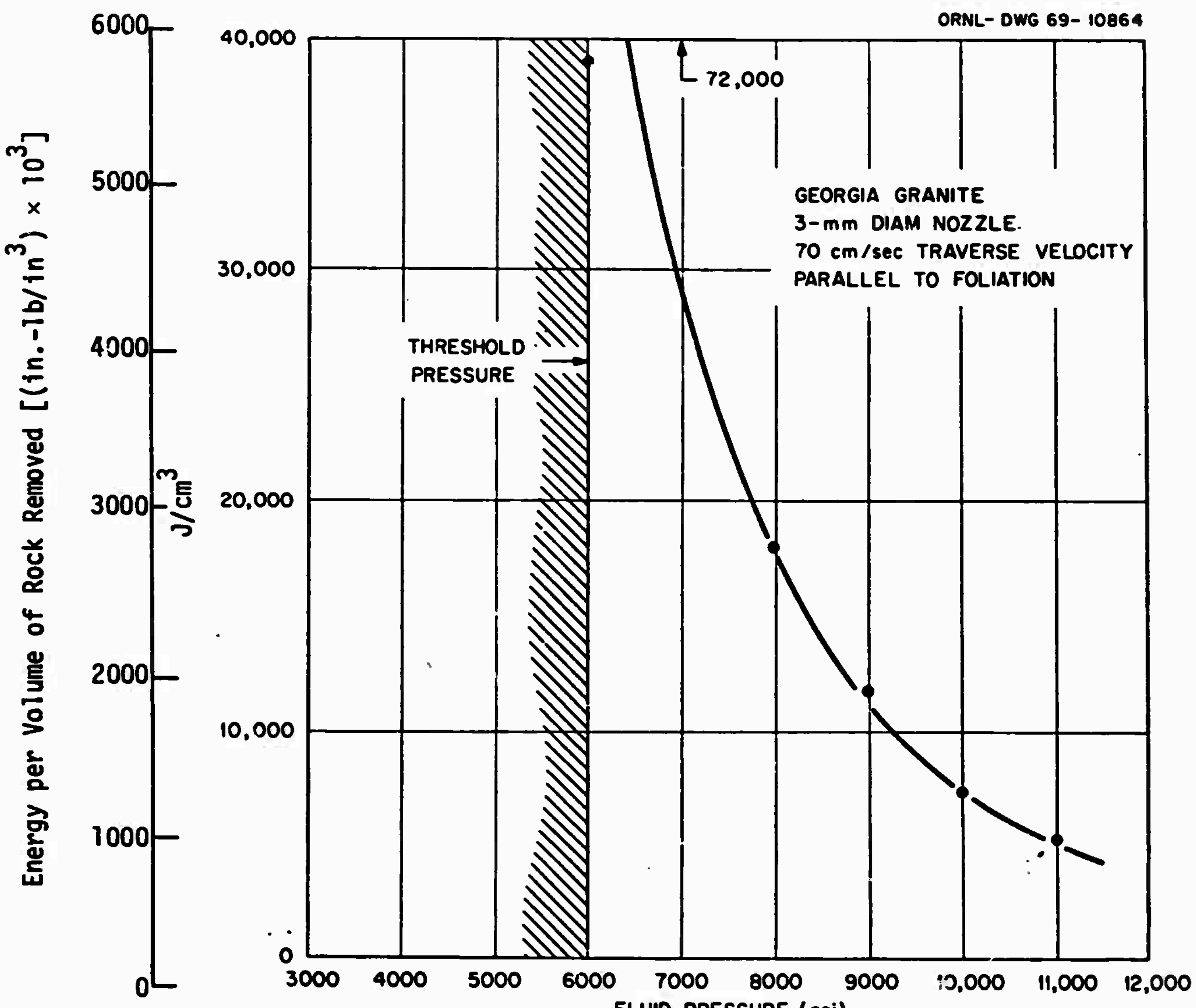

Figure 26. Energy per Volume of Rock Removed as a Function of Fluid Pressure for Georgia Granite[32]

The rate of penetration, R, of a water jet device* can be expressed as

$$R = \frac{P}{AE}$$

where P = jet power

A = tunnel cross-section area

E = energy per volume of rock broken of the device

The jet power (kinetic energy per unit time) is given by:

$$P = w\frac{V^2}{2} = \frac{\pi d^2 \rho V^3}{8}$$

where w = mass flow rate

V = jet velocity

d = nozzle diameter

ρ = fluid density

The jet power may also be expressed in terms of nozzle reservoir pressure:

$$P = \frac{\pi\sqrt{2}d^2 p^{3/2}}{4\sqrt{\rho}}$$

---

*Penetration by a multiple jet device may be approximated by multiplying by the number of jets. Proper spacing of jets would be likely to improve performance over that for a set of jets each having an independent effect on the rock. Possible improvement by multiple, simultaneous, properly spaced water jets has not been investigated. By analogy to boring machine cutter spacing, one concludes that significant improvement may be possible.

where p = nozzle reservoir pressure, or, for water, simply

$$P = 0.0571\ Ap^{1.5}$$

where A = nozzle cross-section area (in^2).

The total power required to operate a fluid jetting device goes up rapidly with increases in jet velocity or nozzle diameter. To achieve efficient breakage of rock, a large-diameter jet at high velocities appears essential but the resultant power requirement is prohibitive. To produce a jet at 200,000 psi continuously through a 0.4-in. nozzle requires approximately 250,000 hp.

To avoid this high power requirement of a large-nozzle, high-pressure, continuously jetting system, Singh and Huck,[33,34] Cooley et al.,[35] and others have selected the mode of intermittent jet pulses rather than continuous flow as a possibly more feasible method of hydraulic rock fragmentation.*

Representative data from single pulse impact on rocks of various strengths are given in Fig. 27 for some of the harder (greater than 10,000 psi) rock samples tested. The data of Leach and Walker[36] included in this figure have been calculated from their reported depths of penetration, assuming penetration cavities to be cylindrical holes of 5 mm diameter as stated in their paper. Other data are from the researcher's own volume and energy calculations.

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*One recently completed prototype design for a pulsed water-jet for rock tunneling experiments calls for a jet at pressures of 300,000 to 1,000,000 psi frequency of one pulse every 5 minutes (or modified to fire 20 pulses per minute), and energy per pulse of 93,500 ft-lb. The jet diameter is 0.27 inch. Prototype fabrication will be funded by the U.S. Department of Transportation, Office of High Speed Ground Transportation.

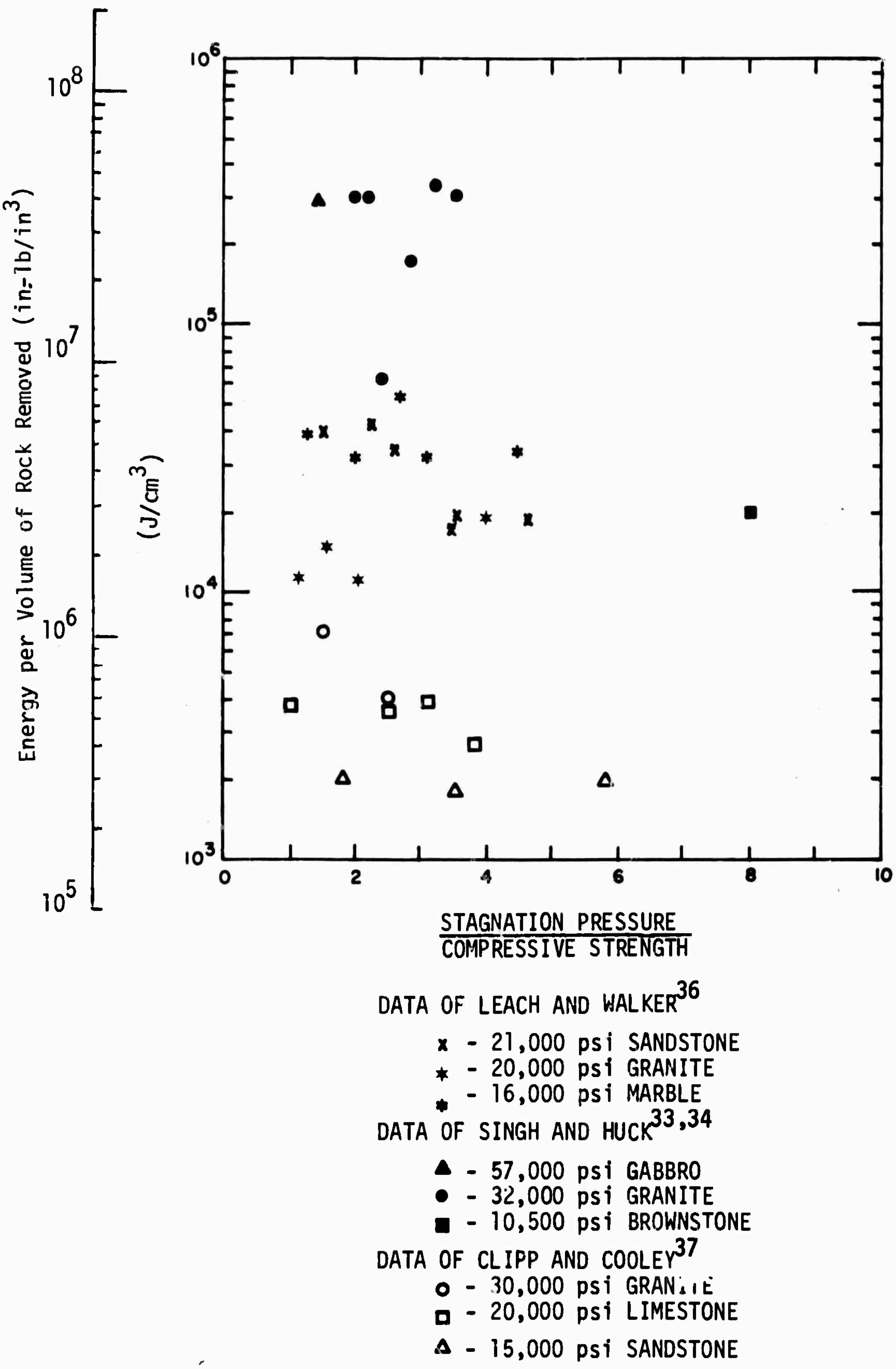

Figure 27. Representative Single-Pulse Water Jet Performance

It can be seen that there is considerable scatter of data for a given jet device and rock type. There does not appear to be any clearly observable trend toward lower energies with higher pressures for a given rock type. This contrasts with the observations of Clipp and Cooley,[37] who report a steady decrease in energy per volume (see Fig. 28, adapted from Ref. 37). This figure shows another effect also observed by other experimenters: multiple shots at the same target, particularly when directed close to an exposed edge or other free surface, significantly reduce the energy requirement to fragment the rock.

Both continuous and pulsed jet performance degrade with increasing distance between the nozzle and the rock face. For standoff distances less than about 500 nozzle diameters, the dispersion of the jet and degradation of impact pressure is apparently not significant. As distance is increased further, however, the total force of impact of the jet on the surface begins dropping rapidly. The results of Semerchan et al.[38] for jets of 500, 1000, and 1500 kg/cm^2 (approximately 7100, 14,200, and 21,300 psi, respectively) indicate at least a 50% reduction in the momentum of the jet at a standoff distance of 1500 nozzle diameters.

No value for the high noise level which is present during water jet operation has been found in the literature surveyed, but it has been discussed by researchers and observers of water jet operation as a possible drawback to the use of high-velocity jet devices in a tunnel environment. Similarly, there is no information published of which the authors are aware that identifies the partitioning of the kinetic energy of the jet when it impacts on the rock. It is unlikely that more than 25% of the jet energy would be transferred to the rock undergoing fragmentation. Analogous considerations of solid pellet impact have shown that this transfer of energy may be as low as 10 to 15%. The waste energy would enter the tunnel environment primarily as thermal energy and would impose an added requirement on the environmental control system to remove it.

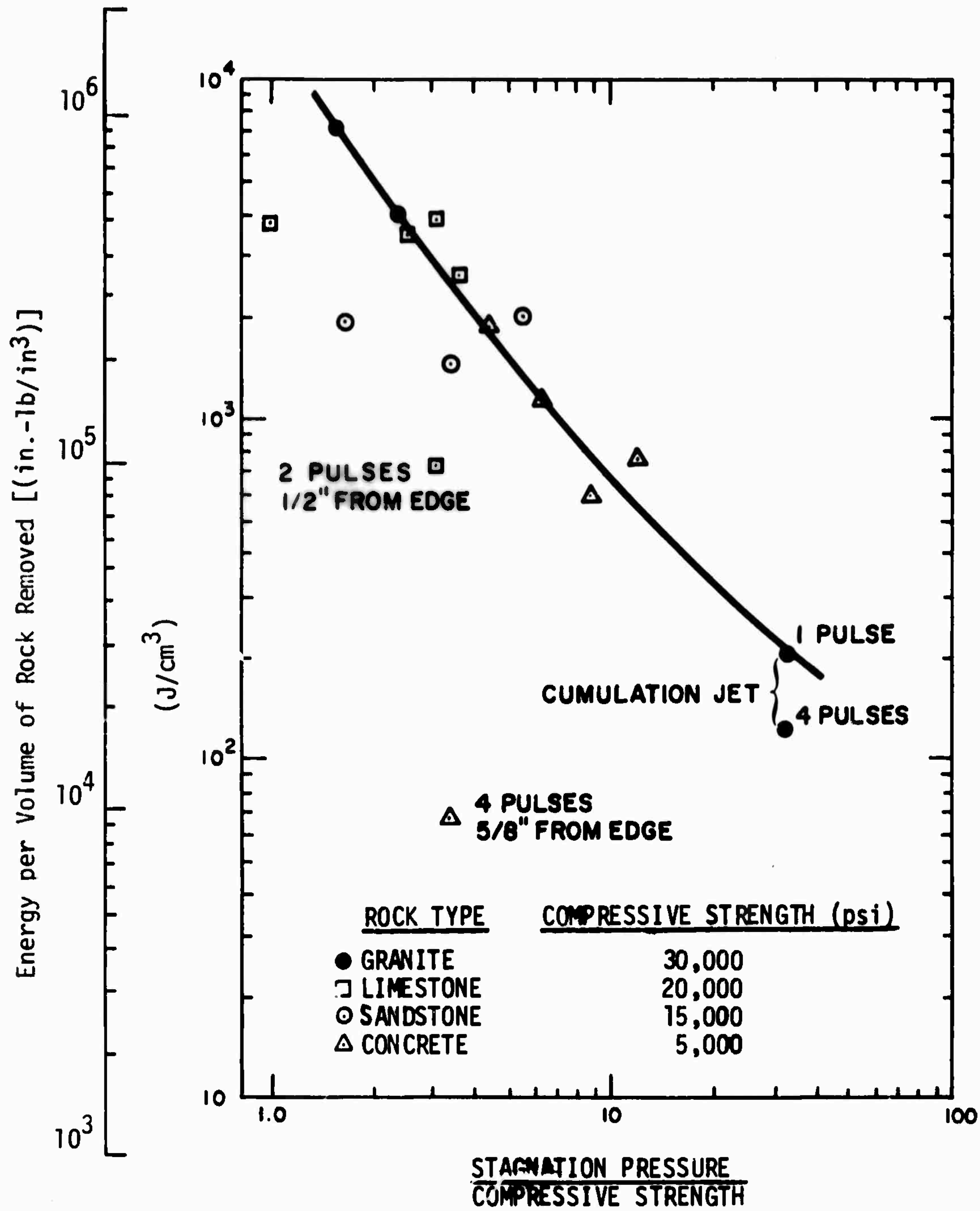

Figure 28. Effect of Jet Pressure on Energy Required to Break Rock[37]

The other water jet operation activities (reposition and aligment, and general maintenance and repair) will be treated in a manner similar to the auxilliary activities of boring machine operation and drill-and-blast operation. No representative cost or time values for these activities have been estimated as yet.

(2) Cost

At this time the only costs identified associated with water jet operation are some tentative capital costs of the equipment. Costs associated with the other elements of the excavation system which are compatible with water jet rock disintegration will be developed during Phase II of the study. It is proposed to model the other operating costs, i.e., direct labor, job materials, by analogy with existing equipment after discussions with people involved in technique research.

d. Element: Rock Disintegration

General Process: Pellet Impact

Activities: Reposition and Align

Pellet Impact

Barrel Replacement

General Maintenance and Repair

Solid pellets, which can be fired at high velocity from rapid-fire guns using gas or solid propellant as an energy source, can impact the hardest rock and fracture it by a conversion of kinetic energy into high pressure in the impact region.

(1) Performance

The required energy per volume of rock broken of the impact process based on the available kinetic energy of the incoming pellet, can be calculated from experimental results[39,40] to be:

$$E = 4.1 \times (10^3)\rho_r^{1.6}\rho_p^{-0.60}E_p^{-0.19}$$

where E = energy per volume of rock broken (J/cm^3)

ρ_r = rock density (g/cm^3)

ρ_p = projectile density (g/cm^3)

E_p = projectile energy (ergs)

The projectile energy, E_p, can be calculated from its velocity, V_p, and its mass, M_p:

$$E_p = \frac{1}{2}M_pV_p^2$$

Figure 29 presents representative energy curves calculated by Physics International for various projectiles and projectile velocities.

Results of Physics International's initial experiments using a gun with a bore diameter of 1 1/2 in., with methane-oxygen propellant,* are consistent with the published work of others. The energy efficiency of the granite impacts was about 90 J/cm^3 (13 × 10^3 in.-lb/in^3). It should be noted that 3 1/2 times the projectile energy was required as chemical energy in the propellant, or an efficiency of gun operation of about 0.29. Further waste of energy occurred upon impact when only 10 to 24% of the projectile kinetic energy was expended for fragmentation, the remainder being expended as waste heat and fragment kinetic energy. Thus, for this method of pellet firing and impact, for every 100 units of chemical power supplied as propellent, 93 to 97 units of waste heat would have to be removed by the combination of gun coolant and environmental control.

*Other means of pellet propulsion are being sought for safer use in a tunnel environment.

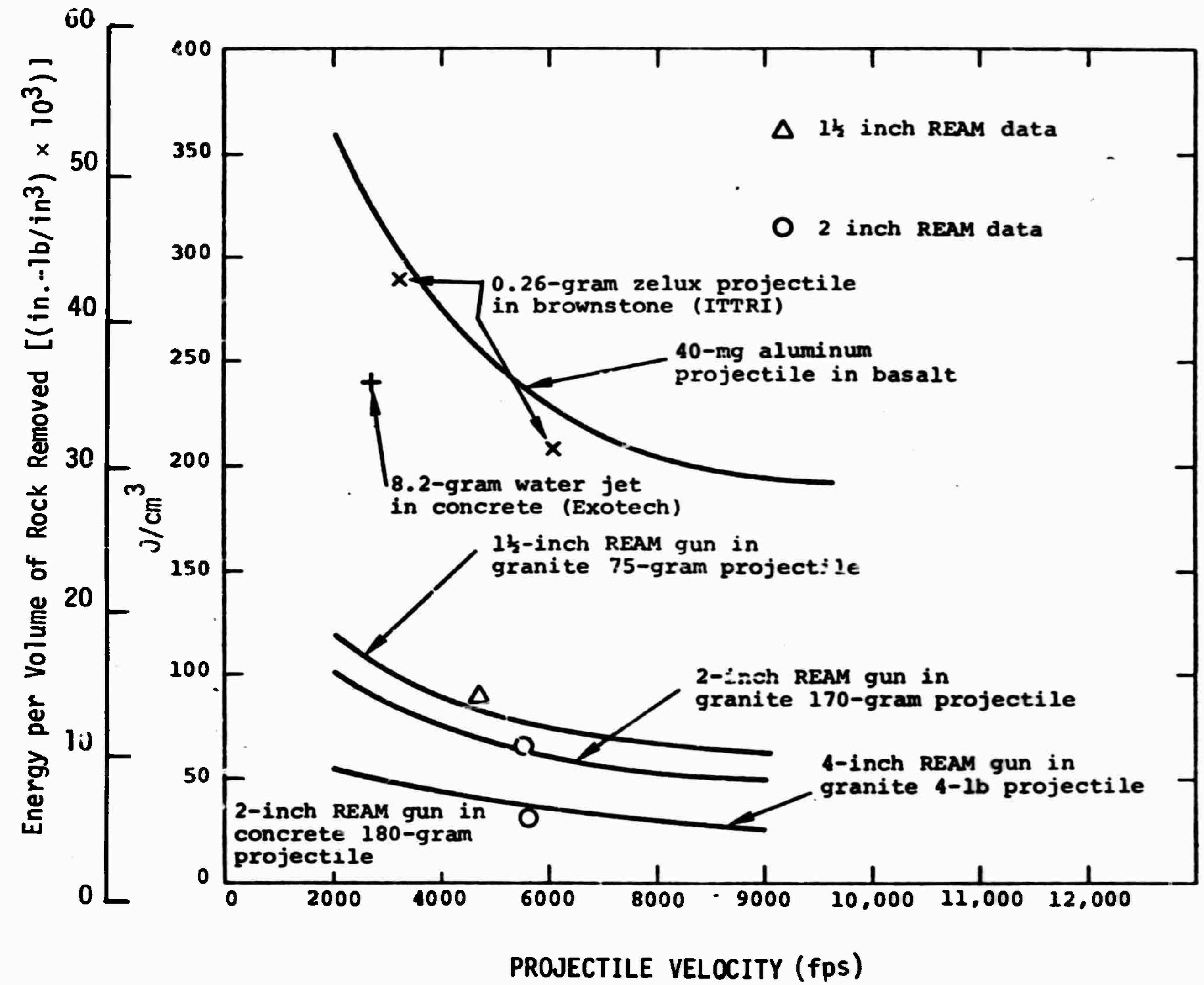

Figure 29. Energy per Volume of Rock Removed as a Function of Projectile Velocity for Various Mass Projectiles, Based on Single Impact Data[40]

The other activities of pellet gun operation are to be treated in a manner similar to water jet operation.

(2) Direct Labor Cost*

The direct labor involved in the gun operation as a function of the tunnel is as follows:

Diameter 10 ft	Diameter 20 ft
1 gun operator	2 gun operators
1 gun loader	2 gun loaders
1 electrician	1 electrician
1 mechanic	1 mechanic
1 miner	2 miners

The number of personnel required for materials handling and ground support will depend on the rate of advance, a function of the rate of firing of the gun, which gives the rock volume rate of material removed from the tunnel face. This relationship has not yet been derived.

(3) Job Material Cost*

The main job materials used in this method are the projectiles used to break the rock.

$$\text{Cost of Job Materials} = \text{Rate of Fire} \times \text{Duration of Firing} \times \text{Projectile Unit Cost}$$

*The estimates are for the Physics International REAM technique of tunnel driving by pellet impact. Since this is a novel technique, the results are subject to greater uncertainties than the methods presently used. The results shown in Ref. 40 are for a complete excavation system (including all the elements), and it is necessary to extract from these results those relevant to the rock disintegration process above, since it is desired to have several options available for the other elements, in order to determin which is the optimum system. Of necessity, therefore, the cost analysis of this process must be handled on on overall general process level rather than on an activity level.

Other equipment costs include barrel replacement costs, power, and compressed air.

$$\text{Barrel Replacement Cost} = .26 \times \text{Cost of Projectiles}$$

$$\text{Other Costs} \approx \$25/\text{hr}$$

3. Plant and Equipment

The estimated cost of one cannon is $180,000 with a 10,000-hour lifetime.* The small amount of ancillary drilling and miscellaneous equipment (including compressed air equipment) supporting the rock disintegration process costs approximately $50,000 for a 10-foot tunnel, and $90,000 for a 20-foot tunnel.

4. Permanent Materials

None

e. Element: Materials Handling

The general processes examined for materials handling are given in Table 11. They have been grouped by function according to those used to transport muck from the excavation face to the main line, and those used as the main line (or long-haul system) to transport muck along the tunnel to a discharge point at a shaft or portal. The main-line systems are also divided according to whether material is transported continuously or intermittently in individual unitized modules. Some of these systems can also be used for transporting men and construction material to and from the tunnel face.

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*Selected arbitrarily to allow amortization to be comparable to that for a tunnel boring machine. The authors have not found data to support any particular value for water cannon lifetime.

At this time consideration has been focused on systems best suited for horizontal transport along a tunnel. Vertical systems for material handling in shafts are not included although it is realized that some of those given in Table 11 can be used for both types of transport.

Continuous main-line general processes include mechanical conveyors, hydraulic pipe, and pneumatic pipe. All these are similar in that an independent medium (i.e., a belt or fluid) normally moving through a closed loop is used to transport the muck continuously from a loading point at or near the face of a tunnel to a discharge point at a portal or shaft. These continuous systems are normally designed to transport muck only; therefore, a supplemental intermittent type system is generally needed for transporting construction materials and personnel.

Conveyor systems typically use a belt-on-roller mechanism as the transporting medium. Presently, their performance (measured in terms of tonnage rate of muck handled) is limited by belt speed, equipment durability, and the fact that shutdowns of the complete system are normally required for belt extension and splicing.

Hydraulic pipe systems transport muck using water pumped through pipelines at a velocity sufficient to propel the muck (normally crushed to form a slurry with the water) along the pipe. This system has had limited application to tunneling, particularly in hard rock, but it has been used as a relatively low-cost method for moving large quantities of bulk materials in the mining and dredging industries where continuous operation over long periods is possible.

The potential of hydraulic systems in rapid tunneling applications is presently limited by the inherent difficulties in extending the system without complete shutdown, and by rapid wear of the transport pipe when the transported rock is highly abrasive. The necessity of having small rock particles to form a slurry will normally require secondary crushing

equipment. Therefore, installing the system in the near face zone would tend to be rather complex. Crushers and mixing tanks must be advanced as well as pipe segments, and all this tends to disrupt flow. Also, the use of large quantities of high-pressure water in a tunnel may be undesirable because of the hazard of flooding.

The pneumatic pipe system exhibits even greater inherent difficulties related to rapid hard rock tunneling. In this system the transporting medium is air drawn or blown through a pipe at velocities sufficient to propel the material along. Although system extension tends to be less complex, the material that can be transported is presently limited to dry, low-density, small-size materials. Also capacities and haul distances presently tend to be low, whereas capital equipment and operating costs are relatively high compared to other systems.

Intermittent general processes for main-line transport include rail systems and truck systems. The distinguishing characteristic of these compared to continuous flow is the separation of materials into discrete quantities which are carried by mobile units, either individually or in interconnected trains.

By the truck system is meant a fleet of rubber-tired, self-propelled vehicles that travel unconstrained in the tunnel. Rubber-tired vehicles are generally considered more practical for tunnel excavation because they are faster than the alternative track-type vehicles (e.g., bulldozers). Presently, truck systems are limited as a potential material handling system in rapid tunneling by their generally unfavorable payload to total volume ratio, by their need for firm, well-graded roadways, and also by their need for individual drivers for each vehicle.

Conventional rail systems consist of modules or cars on wheels that ride on guideways or tracks similar to those of a commercial railroad. Systems presently in use utilize diesel or battery-powered cable drive,

particularly for steep grades, or side-wheel drive. The cable-drive system is not generally considered practical for long-haul, horizontal transport.

Conventional rail systems for material handling in rapid hard rock tunneling are presently limited by such factors as slow and inaccurate track-laying methods, inability (except for cable drive) to climb grades steeper than 4%, manual control that leads to scheduling problems, and slow loading procedures at the tunnel face.

Other rail systems such as monorail and side-rail systems are similar in the sense that each consists of modules that run on rails or guideways. The monorail utilizes a single steel beam mounted above the load-carrying vehicle, whereas the side-rail system utilizes two rails at the sides of the load-carrying vehicle. The module may be driven as a unit or coupled into trains. Both systems normally run above the tunnel floor, limiting their capacity and increasing their equipment cost because of structural support considerations. Support also makes the extension of these systems during rapid excavation operations difficult and time consuming.

Derivation of performance and cost relationships for material handling systems is presently in progress. The activities that are being investigated are as follows.

General Process: Face-to-Main Line Transport
- Shuttle Cars
- Loaders
- Scoop-Trams (Load-Haul-Dump Equipment)
- Shovels
- Trucks
- Tunnel Boring Machine Integrated System

Activities: Load
Transport
Store
Unload
Return
General Maintenance and Repair
Continuously Convey (Continuous Systems Only)
Traffic Delay

General Process: Main-Line Transport (Continuous)
Conveyors
Hydraulic Transport
Pneumatic Transport

Activities: Continuously Convey
Extend System
General Maintenance and Repair

General Process: Main-Line Transport (intermittent)
Rail Systems
Truck Systems

Activities: Load
Transport
Traffic Delay
Unload
Return
Extend System
General Maintenance and Repair
Store

f. Element: Ground Support and Tunnel Lining

General Processes: Rock Bolts
Steel Rib Sets
Shotcrete
Concrete (poured in place)
Concrete (preformed segments)

The analysis of ground support and tunnel lining activities as associated with the above processes is presently in progress. In general, these activities are expected to consist of (1) preparation of the tunnel for ground support, and (2) installation of support material.

g. Element: Environmental Control

General Processes: Ventilation, Temperature Control, Ground Water Control, Dust Control, Auxiliary Service Supply

Activities: Ventilate
Cool (or Heat)
Pump
Extend Service

The analysis of environmental control requirements is also in progress at this time. In most cases modeling is expected to be straightforward, accounting for machinery costs and power usage to meet the needs of the particular tunnel under investigation by comparison with past environmental control systems used to meet similar demands.

The amount of ventilation required for a tunnel will depend on the amount of diesel horsepower used underground, the ambient temperature, and the number of personnel in the tunnel. State requirements on the

number of cubic feet of air per minute per diesel horsepower varies between 50 and 100 cubic feet and must be specified for the excavation simulation to satisfy the established requirement. In addition, state requirements generally specify the minimum required cubic feet of air per minute for each employee underground. Colorado mining laws, for example, specify that the contractor shall provide at least 100 cubic feet per minute of free air for each employee underground and an air velocity of at least 30 linear feet per minute in working places.[41]

Temperature control is of importance in deep tunnels where the ambient rock temperature may exceed 100°F and in tunnels being excavated by systems which produce a significant amount of heat as a by-product of the rock-breaking process. In such circumstances it is necessary to account for the cost of transferring the thermal energy outside of the tunnel to maintain a suitable working environment within the tunnel. The analytical work in progress at this time will attempt to identify this cost as a function of heat transfer rate.

The extension of auxiliary services includes lighting, communications, water, sewage, and fire extinguishing service. This activity is of secondary importance to overall system cost and performance and will be routinely modeled.

APPENDIX I

GENERAL PROCESSES AND ACTIVITIES OF EXCAVATION

A partial list of generalized functions and variables to be considered for tunneling model development

HIERARCHY	GENERAL RELATIONSHIPS REQUIRED	
ELEMENT PROCESS ACTIVITY	FUNCTION (OUTPUT)	VARIABLE (INPUT)
ROCK DISINTEGRATION		
Boring machine	Labor cost Plant and equipment cost	Assigned labor, labor rates, working time Machine cost, machine lifetime, operating hours
Reposition and align	Machine utilization	Advance since last positioning, machine stroke, repositioning time
Bore	Rock volume, volume rate, heading advance, advance rate, machine utilization	Machine power, tunnel diameter, rock strength, machine rock breaking efficiency, power rate
Cutter replacement	Machine availability, job material cost	Cutter replacement frequency, rock type, rock strength, replacement time, cutter cost
General maintenance and repair	Machine availability, job material cost	Maintenance frequency, maintenance time, repair parts cost
Change bore diameter	Machine availability	Tunnel diameter change, change time
Assemble	Machine availability	Assembly time
Disassemble	Machine availability	Disassembly time

Drill and blast	Labor cost Plant and equipment cost	Assigned labor, labor rates, working time Drill and jib cost, characteristics, lifetime, operating hours
Set alignment	Equipment utilization	Repositioning time
Drill holes	Drill rate, job material cost, equipment utilization	Drill power, hole diameter, rock strength, drill efficiency, power cost, number of holes, number of drills, etc.
Load and set charge	Equipment utilization, job material cost	Powder factor: number of holes, explosive per hole; explosive type & cost, loading time
Blasting	Rock volume, heading advance, effective cross-section excavated	Hole depth, overbreakage, tunnel diameter
General maintenance and repair	Job material cost, equipment availability	Bit cost, bit life, hole depth, number of holes, number of drills, maintenance time
Pellet impact	Labor cost Plant and equipment cost	Assigned labor, labor rates, working time Pellet gun cost, gun lifetime, operating hours
Reposition and align	Equipment utilization	Heading advance since last repositioning, repositioning distance, repositioning time
Pellet impact	Rock volume, volume rate, heading advance, advance rate, job material cost, thermal energy rate into environment, equipment utilization	Gun power, firing rate, rock density, pellet density, rock breaking efficiency, power rate, pellet cost

Barrel replacement	Equipment availability, job material cost	Barrel replacement frequency, firing rate, cumulative firing duration
General maintenance and repair	Equipment availability, job material cost	Maintenance frequency, maintenance time, repair parts cost
Water jet	Labor cost Plant and equipment cost	Assigned labor, labor rates, working time Water jet equipment cost, equipment lifetime, operating hours
Reposition and align		Heading advance since last repositioning, repositioning distance, repositioning time
Jet impact	Rock volume, volume rate, heading advance rate, thermal energy rate into environment, equipment utilization	Jet power, jet firing rate, rock strength, rock breaking efficiency, power rate
General maintenance and repair	Equipment availability, job material cost	Maintenance frequency, maintenance time, repair parts cost
MATERIALS HANDLING		
Face-to-main-line transport (intermittent) types: shuttlecars, loaders, scooptrams, shovels, truck	Labor cost Plant and equipment cost	Assigned labor, labor rates, working time Total plant and equipment investment, equipment characteristics, depreciation rate
Load	Volume, volume rate, equipment utilization, job material cost	Load time per unit, volume capacity per unit, number of units, material characteristics, power, power rate

Transport	Equipment utilization, job material cost	Speed of transport, number of units, distance to mainline, power, power rate
Unload	Equipment utilization, job material cost	Unload time per unit, number of units, power, power rate
Return to heading	Equipment utilization, job material cost	Speed of return, number of units, distance from mainline, power, power rate
Traffic delay	Equipment availability	Delay duration
General maintenance and repair	Equipment availability, job material cost	Maintenance frequency, maintenance time, repair parts cost
Face-to-mainline transport (continuous) type: tunnel boring machine integrated conveyor	Labor cost	Included in boring machine assigned labor cost
	Plant and equipment cost	Included in boring machine cost
Transport	Volume rate	Boring machine advance rate, tunnel diameter, material characteristics
General maintenance and repair	Equipment availability, job material cost	Maintenance frequency, maintenance time, repair parts cost
Main-line transport (intermittent) types: rail system, truck system	Labor cost	Assigned labor, labor rates, working time
	Plant and equipment cost	Total plant and equipment investment, depreciation rate, equipment characteristics

Load	Volume, volume rate, equipment utilization, job material cost	Load time per unit, volume capacity per unit, number of units, material characteristics, power, power rate
Transport	Equipment utilization, job material cost	Speed of transport, number of units, distance to portal, power, power rate
Unload	Equipment utilization job material cost	Unload time per unit, number of units, power, power rate
Return to heading	Equipment utilization, job material cost	Speed of return, number of units, distance to heading, power, power rate
Traffic delay	Equipment availability	Delay duration
Extend system	Job material cost, equipment availability	Extension rate, extension length, track cost
General maintenance and repair	Equipment availability, job material cost	Maintenance frequency, maintenance time, repair parts cost
Main-line transport (continuous) types: conveyors, hydraulic pipe, pneumatic pipe	Labor cost	Assigned labor, labor rates, working time
	Plant and equipment cost	Plant and equipment investment, depreciation rate, equipment characteristics
Secondary crushing	Volume rate, equipment utilization, job material cost	Rock fragment size, strength, crushing efficiency, power, power rate
Transport	Volume rate, equipment utilization, job material cost	Motor, pump or blower power, power rate

Extend system	Job material cost equipment availability	Rate of extending, reach length, conveyor of pipe cost
General maintenance and repair	Equipment availability, job material cost	Maintenance frequency, maintenance time, repair parts cost
GROUND SUPPORT AND TUNNEL LINING		
Initial support, types: rock bolt, steel rib set, shotcrete	Labor cost Plant and equipment cost	Assigned labor, labor rates, working time Plant and equipment investment, depreciation rate, equipment characteristics
Requirement assessment	Support type, spacing, thickness	Rock type, geologic structure, joint spacing, joint direction, water inflow, cover over tunnel
Installation	Installation rate, permanent material cost, equipment utilization	Material transport time, assembly or installation time, support type, spacing or thickness, tunnel diameter, material cost per pound
Lining, types: poured concrete, concrete segments	Labor cost Plant and equipment cost	Assigned labor, labor rates, working time Plant and equipment investment, depreciation rate
Installation	Installation rate, permanent material cost, equipment utilization	Material transport or preparation time, assembly or installation time, material unit cost, cure time (poured concrete)

ENVIRONMENTAL CONTROL		
Ventilation	Labor cost	Assigned labor, labor rates, working time
	Plant and equipment cost	Cost of fans and ducting, length of tunnel, depreciation rate, air flow required for, (number of men, diesel hp at heading)
	Job material cost	Fan motor power, operating time
Temperature control	Plant and equipment cost, job material cost	Rock surface temperature, thermal energy transferred into tunnel from rock fragmentation, materials handling, ground support activities, cost per unit of thermal energy transferred out of tunnel
	Labor cost	Assigned labor, labor rates, working time
Ground water control	Labor cost	Assigned labor, labor rates, working time
	Plant and equipment cost, job material cost, permanent material cost	Water inflow rate, pump cost, depreciation rate, grouting requirement, grouting unit cost, power, power rate
Extension of auxiliary services (e.g., lighting)	Labor cost	Assigned labor, labor rates, working time
	Job material cost, equipment availability	Extension rate, extension length, material unit cost

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TUNNELING MACHINE

No.	Date	Manu-facturer	Model	Type	Rotation hp	Hydraulic Pump Motor hp	Thrust lb	Torque ft lb	Cutters	Number of Cutters	Stroke Ft	Weight tons	Cost 1965 $	Location	Diameter ft	Area ft^2	Length ft	Appli
1	1953	Robbins	910	Jumbo	400	50	180,000	281,000	drag bite diec rollere			125	450,000	Oshe Dam, S.Dakots, U.S.A.	25.8	520		hydro alect
2	1955	Robbins	930	Jumbo	400	50	192,500	360,000	drag bits diac rollere			130	485,000	Oahe Oam, S.Dakota, U.S.A.	26.2	541	23,000	hydro-alect
3	1955	Robbins	101	Gripper	310	80	117,600	138,000	drag bits diec rollers			17		Pittsburgh, U.S.A.	8.0	50.3		aewer
4	1955	Robbins	102	Gripper	310	80	117,600	107,000	drag bits disc rollers			17		Pittsburgh, U.S.A.	8.5	56.5		eewer
5	1955	Robbins	103	Gripper	310	80	117,600	138,000	dreg bits diec rollere			17		Chicego, U.S.A.		63.6		eewer
6	1956	Robbins	131	Gripper	340		314,000	176,000	disc rollers			65		Toronto, Canads	10.8	91.1	14,800	eewer
7	1957	Robbins	103	Gripper	310	80	117,600	138,000	drag bits diec rollers			17		Canada	9.0	63.6		mine
8	1958	N.C.B.			750		990,000		gear rollers			300	850,000	Breedon, U.K.	18.0	254		exp.
9	1958	N.C.B.			750		990,000		geer rollere			300	850,000	Dragonby, U.K.	18.0	254		mine
10	1958	Hughes			75		226,000		gear rollers			8		U.S.A.	3.3	8.7		exp.
11	1959	Robbins	351	Jumbo	680		250,000	684,000	drag bits diec rollere	45		175	580,000	Oshe Oam, S. Osk., U.S.A.	29.5	684	7,700	hydro-electr
12	1960	Robbine	161	Gripper	600	26	750,000	762,000	diec rollers	34		105	550,000	Taemenia	16.1	203	14,600	hydro-alectr
13	1961	Robbins	261	Jumbo	900	75	500,000	3,500,000	drag bits			175		Saeketchewan, Canade	25.7	517	20,000	hydro-electr
14	1961	Hughes			1000		1,500,000		drag bits disc rollera			320		Mangla Dam, W. Pekieten	36.7	1050	8,500	hydro electr
15	1962	Robbins	71	Gripper	100	20	500,000	100,000	diec rollere			25		Virginia, U.S.A.	7.0 7.5	38.5		eewer
16	1962	Robbins	371	Jumbo	1000		600,000	1,000,000	drag bits	154		225		Mangla Dam W. Pakistan	36.7		8,500	hydro-electr
17	1962	Robbine	341	Shield	1000		150,000		disc rollera			550	1,500,000	[illegible], France	33.7	892	7,400	metro
18	1963	Robbina	71A	Gripper	150		500,000	115,000	disc rollere			27		Homer Waueeca, U.S.A.	7.0	38.5		mina
19	1963	Hughea			250		600,000		gear rollere			35		Mogollon Rim, U.S.A.	6.7	34.9	5,300	hydro-electr
20	1964	Lawrence	HRT-12		600		1,500,000	350,000	button rollere			70		New York, U.S.A.	12.0	113	400	water
21		Jarva		Gripper	225		43,000		button rollers			25		Philedelphia U.S.A.	6.0	28.3		sewer
22	1964	Robbins	72	Gripper	150				disc rollers					Shikoku Is. Japan	7.0	38.5		
27	1965	Robbins	61-113	Gripper	200		315,000		disc rollers		3	33	200,000	Br.Columbia Canada	8.5	56.5	26,000	hydro-electr
24	1964	Robbine	73	Gripper	150				diec rollere					Arizona, U.S.A.	7.0	38.5	111	water
25	1964	Robbins	74	Gripper	150		200,000		disc rollere			36	200,000	Beeeems, France	7.2	38.5		water
26	1965	Jarva	Mk 8	Gripper	300	25	560,000	133,000	button rollers	17		28	330,000	St. Louis, U.S.A.	7.8	48.1	10,000	sewer
27	1965	Robbins	81-118	Gripper	200		315,000		disc rollers				200,000	Freiberg, Switzerland	8.5	56.5	7,000	sewer
28	1965	Robbine	121	Gripper	400		480,000	300,000	disc rollers	25-29	3.5	76	400,000	Azotea, U.S.A.	11.8 13.5	109 143	67.000	water
29	1965	Robbins	111-117	Gripper	400		430,000		disc rollers			72	350,000	[illegible]en, Switzerland	11.5	104	8,200	water
30	1965	Jarva	Mk 14	Gripper	500	40	866,000	275,000	button rollers	27		80	540,000	Philadelphia, U.S.A.	13.7	148	1,600	sewer
31	1965	Calweld							diec rollere					Minneeota, U.S.A.	15.9	199	6,900	sewer
32	1965	Hughee	Betti 1		1000		1,400,000		Gear, diec rollere	43	5	280	1,000,000	Navajo, U.S.A.	19.8 20.8	310 340	10,000	
33	1966	Demag			200		224,000		diec rollere			40		Dortmund, Germany	6.5	33.1	2,600	eewer
34	1966	Robbine	104-120	Gripper	300		372.000	175,000	diec rollere	22-24	3	55		Blanco, Colorado, U.S.A.	9.9 10.6	77.1 88.0	41,800	weter
35	1966	Robbins	104-121A	Gripper	300		372,000	175,000	diec rollere	22	3.3	55	360,000	Oso, U.S.A.	9.9 10.6	77.1 88.0	26,400	weter
36	1966	Jarva	Mk 14	Gripper	500	40	866,000	275,000	button rollere	27		80	540,000	[illegible], U.S.A.	10.5	86.5	4,200	sewer
37	1966	Calweld			200		560,000	320,000	disc rollere					Coventry, U.K.	11.3	101	10,000	sewer
38	1966	Hal egger	836		650		515,000	500,000	dreg bite			85	360,000	Japan	11.5	104	66,000	[illegible] pilot
39	1966	Calweld							diec rollere					Jepan	12.6	124	24,000	
40	1967	Oemeg	TVM 19/23		300							45		Stuttgart, Germany	7.0	38.5	4,600	water
41	1967	Wirth	TBM 214	Gripper	250		400,000	100,000	geer rollers			32		Austria	7.0	38.5	800	water
42	1967	Krupp		Crawler					drag bits			37		[illegible]	[illegible]	[illegible]		

1 B

APPENDIX II - HISTORY OF HARD ROCK BORING MACHINES

TUNNEL					PERFORMANCE										
Length ft	Application	Rock type	Strength ksi	Mohs' hardness	Maximum penetration ft/hr	Rock removed ft^3/hr	$ft^3/hphr$	Specific energy J/cm^3	Operating time %	Maintenance repair %	Changing cutters %	Delays %	Reposition time, min	Cutter change time	
	hydro-electric	shale	0.2-0.4	2	8-12	4100-6200	10.2-15	6.3-9.3	51	10.5	4.3	34.2			Bad ground,
23,000	hydro-electric	shale	0.2-0.4	2	8-12	4100-6200	10.2-15	6.3-9.3	50						Bad ground,
	sewer	shale	5-12	2	6-8	300-400	1.0-1.3	73-94							Excessive dr
	sewer	shale limestone	5-15	2-3	8-10	450-560	1.5-1.8	53-63							Excessive d
	sewer	limestone	18-25	3	2-4	125-250	0.4-0.8	120-240							Excessive dr
14,800	sewer	limestone sandstone shale	8-27		11	1000	2.9	32							Some rock st
	mine	iron ore			10-12	640-760	2.1-2.5	38-45							Chicago proj
	exp.	limestone	18-20	3											
	mine	iron ore	4-8		15	3800	5.1	19							
	exp.	various	3-30		17-20	150-175	2.0-2.3	41-47							
7,700	hydro-electric	shale	0.2-0.4	2	8-12	5500-8200	8.1-12.1	8-12							
14,600	hydro-electric	mudstone	10-17		5-6	1000-1200	1.7-2.0	47-56	63	18	11	8			$6yd^3$ cars; du in one 6 day
20,000	hydro-electric	shale	0.1-0.4	2	5-10	2600-5200	2.9-5.8	16-33							Badly faulted
8,500	hydro-electric	limestone			5-8	5250-8400	5.2-8.4	11-18							
	sewer	iron ore limestone	10-15		10	380-440	3.8-4.4	22-25							
8,500	hydro-electric	shale sandstone	1-8		4-8	5000-8400	5.0-8.4	11-19							
7,400	metro	limestone sand/clay	0-15		3.3	2900	2.9	33							Face under c
	mine	iron ore	8-14		5	190	1.3	73							Cutter and e
5,300	hydro-electric	sandstone	11-15		13	450	1.8	53							
400	water	shale metamorphic rocks	3-28		4	450	0.8	120							Failure due
	sewer	mica schist			4	110	0.5	190							
		chlorite schist	10-20												
26,000	hydro-electric	schist	15-20												
111	water	sandstone	3-7												Project fini
	water	schist	10-18		5	190	1.3	73							
10,000	sewer	limestone chert	12-15		4-7*				40-45						$2yd^3$ cars; cu
7,000	sewer	sandstone	3-7		10	560	2.8	34	57						Second unit
67,000	water	shale sandstone	1-8	2.5	12-18	1300-2500	3.2-6.2	15-30		35	included in maintenance		2	30	241 ft advan conveyor unl
8,200	water	sandstone	1-5		8-20	830-2300	2.1-5.8	16-45							
1,600	sewer	limestone hornblende	6-25		1-8*	150-1200	0.3-2.4	39-300	42						*4.38 ft/hr s costs $54.00
6,900	sewer	sandstone			3	600									
10,000		shale sandstone	5-6	4	10-17	3100-5100	3.1-5.1	19-31	57	10.9	4.9		15	240	200 ft conve 75 min cycle
2,600	sewer	sandstone	4-10		6-9	200-300	1.0-1.5	63-95							
41,800	water	sandstone shale	1-6	2.5-5	14.3	1100	3.7	26	50				2	30	8-16yd^3 cars/ 35-60 min; du best week 175
26,400	water	shale	1-6	2.5-5	17.5	1540	5.1	19		10-15	included in maintenance		0.5	60	11 5yd^3 cars/ dump in 20 mi best week 190
4,200	sewer	limestone	12-19		4*				40						*Average rat
10,000	sewer	sandstone marl	4-12		4	400	2.0	47							
66,000	railway pilot	tuff, andesite	5-34		8	830	1.3	74							
24,000		sandstone clay			4.5	550									
4,600	water	limestone	29		5	190	0.6	150							
800	water	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]							

PERFORMANCE									
Rock removed ft^3/hr	$ft^3/hphr$	Specific energy J/cm^3	Operating time %	Maintenance repair %	Changing cutters %	Delays %	Reposition time, min	Cutter change time	REMARKS
4100-6200	10.2-15	6.3-9.3	51	10.5	4.3	34.2			Bad ground, faulted shale, belt conveyor problems
4100-6200	10.2-15	6.3-9.3	50						Bad ground, faulted shale, belt conveyor problems
300-400	1.0-1.3	73-94							Excessive drag bit breakage
450-[illegible]	1.5-1.8	53-63							Excessive drag bit breakage
125-250	0.4-0.8	120-240							Excessive drag bit breakage
1000	2.9	32							Some rock strengths as high as 27,000 psi
640-760	2.1-2.5	38-45							Chicago project machine
3800	5.1	19							
150-175	2.0-2.3	41-47							
5500-8200	8.1-12.1	8-12							
1000-1200	1.7-2.0	47-56	63	18	11	8			$6yd^3$ cars; dust a major problem; world's record 751 ft in one 6 day week
2600-5200	2.9-5.8	16-33							Badly faulted shale
5250-8400	5.2-8.4	11-18							
380-440	3.8-4.4	22-25							
5000-8400	5.0-8.4	11-19							
2900	2.9	33							Face under compressed air, sealing problems
190	1.3	73							Cutter and access problems, Virginia project machine
450	1.8	53							
450	0.8	120							Failure due to slewing system, hydraulic pumps and anchor
110	0.5	190							
									Project finished soon after machine started
190	1.3	73							
			40-45*						$2yd^3$ cars; cutter costs $6.50-15.00 per ft; *average rate
560	2.8	34	57						Second unit of model 81
1300-2500	3.2-6.2	15-30		35	included in maintenance		2	30	241 ft advance best day, 1035 ft best 5 day week, 300 ft conveyor unloads into 10 side dump cars of $5yd^3$ capacity
830-2300	2.1-5.8	16-45							
150-1200	0.3-2.4	39-300	42						*4.38 ft/hr average rate; cutter costs $54.00/ft
600									
3100-5100	3.1-5.1	19-31	57	10.9	4.9		15	240	200 ft conveyor, 2 trains of 5 cars, 10 yd^3/cars each, 75 min cycle
200-300	1.0-1.5	63-9[illegible]							
1100	3.7	26	50				2	30	8-16yd^3 cars/train, 4 trains, 360 ft conveyor loaded a train in 35-60 min; dump in less than 10 min; best month's advance 6,713 ft best week 1751 ft; 3 Calif. switches
1540	5.1	19		10-15	included in maintenance		0.5	60	11 $5yd^3$ cars/train, 4 trains, conveyor loaded a train in 20 min; dump in 20 min, cycle time 120 min, best month's advance 6,849 ft, best week 1905 ft, best day 419 ft
			40						*Average rate
400	2.0	47							
830	1.3	74							
550									
190	0.6	150							

31	1965	Calweld							disc rollers					U.S.A.	15.9	199	6,900	sewe
32	1965	Hughes	Betti 1		1000		1,400,000		Gear, disc rollers	43	5	280	1,000,000	Navajo, U.S.A.	19.8 20.8	310 340	10,000	
33	1966	Demag			200		224,000		disc rollers			40		Dortmund, Germany	6.5	33.1	2,600	sewe
34	1966	Robbins	104-120	Gripper	300		372,000	175,000	disc rollers	22-24	3	55		Blanco, Colorado, U.S.A.	9.9 10.6	77.1 88.0	41,800	wate
35	1966	Robbins	104-121A	Gripper	300		372,000	175,000	disc rollers	22	3.3	55	360,000	Oso, U.S.A.	9.9 10.6	77.1 88.0	26,400	wate
36	1966	Jarva	Mk 14	Gripper	500	40	866,000	275,000	button rollers	27		80	540,000	St. Louis, U.S.A.	10.5	86.5	4,200	sewe
37	1966	Calweld			200		560,000	320,000	disc rollers					Coventry, U.K.	11.3	101	10,000	sewe
38	1966	Habegger	836		650		515,000	500,000	drag bits			85	360,000	Japan	11.5	104	66,000	rai pil
39	1966	Calweld							disc rollers					Japan	12.6	124	24,000	
40	1967	Demag	TVM 19/23		300							45		Stuttgart, Germany	7.0	38.5	4,600	wat
41	1967	Wirth	TBM 214	Gripper	250		400,000	100,000	gear rollers			32		Austria	7.0	38.5	800	wat
42	1967	Krupp		Crawler					drag bits			37		Germany	9.8	75.8		min
43	1967	Jarva	Mk 8/10	Gripper	300	25	560,000	133,000	button rollers	17		30	330,000	St. Louis, U.S.A.	10.0	78.5	3,500	sew
44	1967	Jarva	Mk 11	Gripper	400	40	866,000	275,000	button rollers	21		45	410,000	Minaville, N.Y., U.S.A.	10.0	78.5	768	mi
45	1967	Robbins	111-117	Gripper	400		430,000		disc rollers			72		Zurich, Switzerland	11.0	95.1		wa
46	1967	Robbins	181	Gripper	1500		1,500,000		disc rollers					Copper, Michigan, U.S.A.	18.0	254		co min
47	1967	Robbins	132	Gripper	400				disc rollers					Melbourne Australia	12.7		55,000	sa
48	1967	Habegger	836		650		515,000	500,000	drag bits			85	360,000	Chur, Switzerland	11.5	104	19,000	hy al
49	1967	Jarva	Mk 14	Gripper	500	40	866,000	275,000	button rollers	27		80	540,000	Cleveland, U.S.A.	13.0	133	1,000	min
50	1967	Calweld										250		Newhall, U.S.A.	25.6	512	18,000	wat
51	1967	Habegger	829		550				drag bits			65		Stuttgart, Germany	9.5	70.7		wat
52	1968	Robbins	371	Jumbo	1000	100			disc rollers					Liverpool, U.K.	34.0	909	7,000	roa
53	1968	N.C.B.			95				disc rollers						6.0	28.3		
54	1968	Habegger	836		650		515,000	500,000	drag bits			85		Japan	11.5	104		ra
55	1968	Habegger	840											Japan	13.2	138		ra pi
56	1968	Jarva	Mk11-12	Gripper							2		450,000	River Mountains, U.S.A.	12.0	113	20,000	wa
57	1968	Robbins	112	Gripper	400				disc rollers					Switzerland	10.8			ro
58	1968	Robbins	82	Gripper	200				disc rollers					Tasmania	8.0			hy al
59	1968	Robbins	122	Gripper	400				disc rollers					Spain	11.8			wa
60	1968	Komatsu	TM 445GS	Gripper & Shield										Japan				
61	1969	Robbins	352-128												35.0			
62	1969	Robbins	142-139	Gripper											14.0			
63	1967	Robbins	81-113	Gripper	200		315,000			20	3	33		Central Utah, U.S.A.	9.5	70.9	5,345	
64	pre 1964	Soviet	PKG-2						rotating bits									
65	1968	Jarva	Mk 21	Gripper	750	60	2,200,000	660,000	button rollers	76		215		San Francisco, U.S.A.	20.0		7,000	ra tr
66	1968	Jarva	Mk 8	Gripper	300	25	560,000	133,000	button rollers	17		28	330,000	Chicago, U.S.A.	8.0	50	18,000	sew
67	1968	Wirth	TB11-300	Gripper					button rollers	26		90		Switzerland	9.8	75	3,700	hyd al
68	1968	Wirth	TBI-240	Gripper						16				Switzerland	7.9	49		ex
69	1969	Wirth	TBI-214	Gripper										Stockholm, Sweden	7.9	49	1,480	sa
70	1969	Atlas Copco												Switzerland	11.2	100	16,000	sew
71	1970	Calweld		Gripper					button rollers					Climax, Colorado, U.S.A.	13.0	133		mi
72	1969	McAlpine																
73	1970	Robbins		Gripper	400									Toronto, Canada	12.0	113	12,000	se

15.9	199	6,900	sewer	sandstone			3	600								
19.8 20.8	310 340	10,000		shale sandstone	5-6	4	10-17	3100-5100	3.1-5.1	19-31	57	10.9	4.9		15	240
6.5	33.1	2,600	sewer	sandstone	4-10		6-9	200-300	1.0-1.5	63-95						
9.9 10.6	77.1 88.0	41,800	water	sandstone shale	1-6	2.5-5	14.3	1100	3.7	26	50				2	30
9.9 10.6	77.1 88.0	26,400	water	shale	1-6	2.5-5	17.5	1540	5.1	19		10-15	included in maintenance		0.5	60
10.5	86.5	4,200	sewer	limestone	12-19		4*				40					
11.3	101	10,000	sewer	sandstone marl	4-12		4	400	2.0	47						
11.5	104	66,000	railway pilot	tuff, andesite	5-34		8	830	1.3	74						
12.6	124	24,000		sandstone clay			4.5	550								
7.0	38.5	4,600	water	limestone	29		5	190	0.6	150						
7.0	38.5	800	water	granite			5	190	0.8	125						
9.8	75.8		mine	shale			12	910								
10.0	78.5	3,500	sewer	limestone	14-19		4*				53					
10.0	78.5	768	mine	hematite gneiss	10-35		1.5*									
11.0	95.1		water													
18.0	254		copper mine	shale sandstone	15-30											
12.7		55,000	sewer	mudstone	5-20											
11.5	104	19,000	hydro-electric	shale quert limestone	14-21		3-6	310-420	0.8-1.0	95-120						
13.0	133	1,000	mine	hematite argillite	10		5*									
25.6	512	18,000	water	sandstone gravel	3-15		4 (est.)	2000 (est.)								
9.5	70.7		water													
34.0	909	7,000	road	sandstone marl	5-10											
6.0	28.3			limestone												
11.5	104		rail pilot													
13.2	138		rail pilot													
12.0	113	20,000	water	rhyolite rhyodacite	17		4.8	542				25			1	30
10.8			road	conglomerate sandstone	4-15											
8.0			hydro-electric	mudstone	10-17											
11.8			water	shale	1-10											
35.0																
14.0																
9.5	70.9	5,345		sandstone siltstone shale			9	638	3.2	30		33			2	30
20.0		7,000	rapid transit	serpentine greenstone chert	3-25		5*									
8.0	50	18,000	sewer	limestone	15-30		6*									
9.8	75	3,700	hydro-electric	granite	34		2.6	196			50	40	10			
7.9	49		exp.	granite	34											
7.9	49	1,480	sewer													
11.2	100	16,000	sewer				3.9	390								
13.0	133		mine	granite schist	35											
12.0	113	12,000	sewer													

1 E

150-1200	0.5-2.4	39-300	42						costs $54.00/ft
600									
3100-5100	3.1-5.1	19-31	57	10.9	4.9		15	240	200 ft conveyor, 2 trains of 5 cars, 10 yd^3/cars each, 75 min cycle
200-300	1.0-1.5	63-95							
1100	3.7	26	50				2	30	8-16yd^3 cars/train, 4 trains, 360 ft conveyor loaded a train in 35-60 min; dump in less than 10 min; best month's advance 6,713 ft best week 1751 ft; 3 Calif. switches
1540	5.1	19		10-15	included in maintenance		0.5	60	11 5yd^3 cars/train, 4 trains, conveyor loaded a train in 20 min; dump in 20 min, cycle time 120 min, best month's advance 6,849 ft, best week 1905 ft, best day 419 ft
			40						*Average rate
400	2.0	47							
830	1.3	74							
550									
190	0.6	150							
190	0.8	125							
910									Crawler mounted
			53						*Average rate; cutter cost $8.00/ft
									*Average rate; 27° inclined shaft
									Same machine as Baden project
									Two hydraulically operated rotary percussive roof pinner drills, two cutters per path, wet scrubber dust collection system
310-420	0.8-1.0	95-120							
									*Average rate
2000 (est.)									
									Same machine as Mangle Dam project
542				25			1	30	
									Robbins licensee, machine is convertible to shield type
									Ropebelt conveyor; best day's advance 105 ft
638	3.2	30		33			2	30	Same machine as 1964 Br. Columbia project 6 5 yd^3 cars/train, 2 trains, 198 ft conveyor
									*Average rate; 37% of cutters lasted to end of job, 50% of cutters lasted > 1000 hrs; cutter costs $30/ft
									*Average rate
196			50	40	10				33° incline; fluid assisted gravity flow of cuttings
									160 ft in 2 weeks
390									*Formerly Habegger

1 F